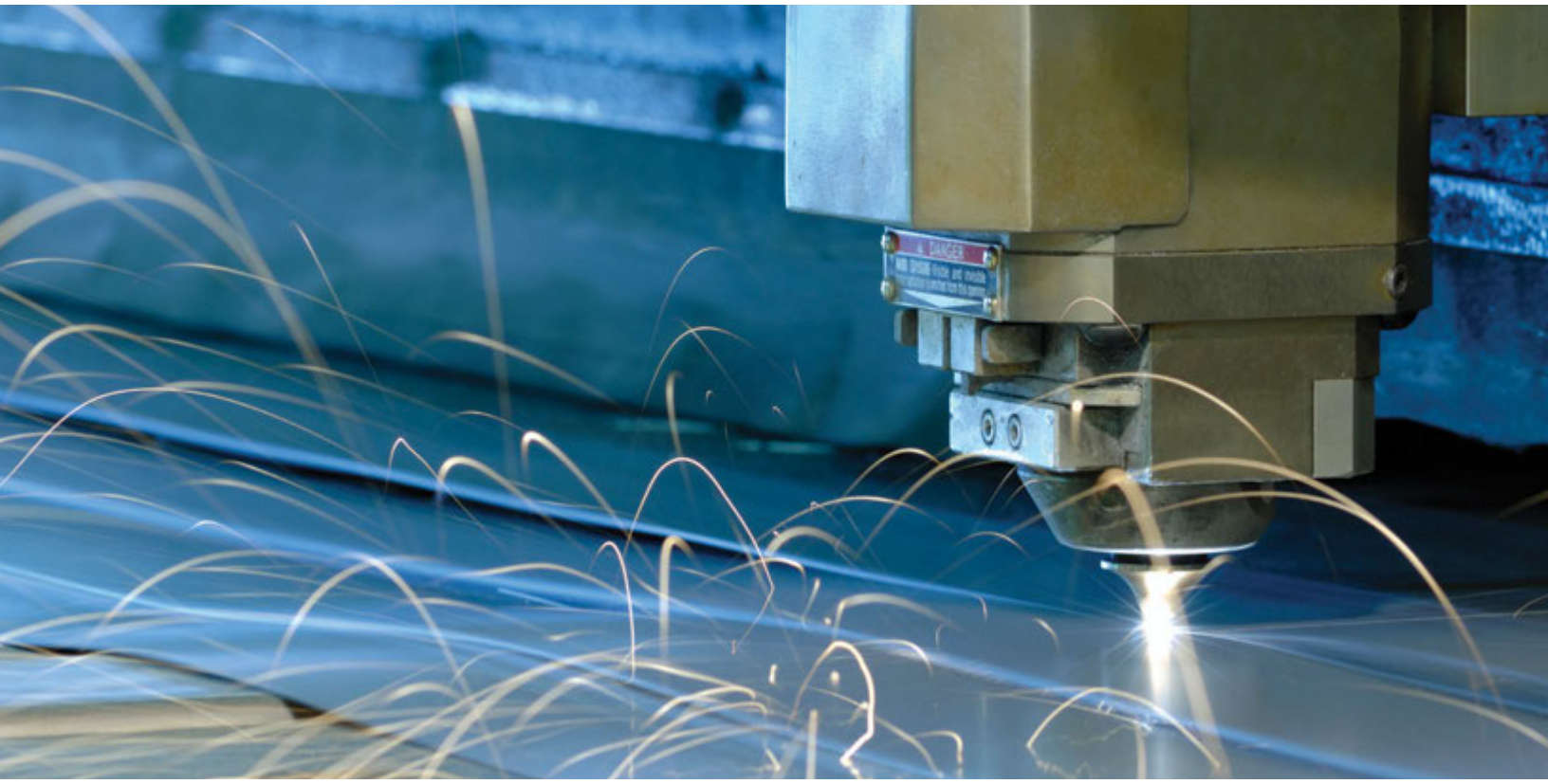
Control and Automation

Solutions Guide



Edition 1, December 2011

MAXIM
INNOVATION DELIVERED®

Control and Automation Solutions Guide

A message from the Senior Vice President, Industrial and Medical Solutions Group

Dear Customers,

Over 28 years ago Maxim was founded with the goal of providing high-quality integrated circuits for the industrial marketplace. We have continued to build on that industrial foundation, with more than 28% of our $2.5 billion in revenue now coming from industrial products. Our original mission has never wavered. We deliver robust, innovative solutions that add value to the products designed and built by our customers.

This *Control and Automation Solutions Guide* focuses on the best Maxim products for each function or type of equipment discussed in the chapter overviews. Chapters highlight five specific functions and types of industrial equipment. One chapter discusses programmable logic controllers (PLCs), which provide highly repeatable machine control. The sensors chapter discusses the complex, wide range of tasks that optimized sensing circuits must perform to ensure that a PLC works efficiently. A chapter on environmental automation presents circuits for the control and monitoring of residential and commercial environments. The motor control chapter discusses the challenges of carefully and efficiently starting, accelerating, decelerating, and stopping large high-powered industrial motors. Finally, the calibration chapter explains how factory and field calibration allows us all to have affordable industrial equipment that is safe and accurate.

But today's new Maxim is more than just great products. We also offer great customer service. To this end, we added a specific focus on the needs of industrial customers to the training given to our direct sales force and worldwide distributors. They understand the technical needs of your products and will provide you high-quality support.

Our entire sales organization welcomes the opportunity to discuss your needs and our products. And I welcome your questions and comments about Maxim and this solutions guide. Let me know what you think. You can reach me at: controlautomation@maxim-ic.com.

Thank you,

Chris Neil
Senior Vice President,
Industrial and Medical Solutions Group

Table of Contents

Programmable Logic Controllers (PLCs)

3 Overview

6 Analog Input Functions
Featured Products

12 Analog Output Functions
Featured Products

21 Digital I/O Functions
Featured Products

24 Fieldbus Functions
Featured Products

30 CPU Functions

31 Nonisolated and Isolated Power-Supply Functions
Featured Products

37 Recommended Solutions

Sensors

49 Overview

50 Pressure Sensors and Weigh Scales (Force Sensing)
Featured Products

57 Temperature Sensing
Featured Products

64 Light Sensing
Featured Products

68 Proximity Sensing
Featured Products

71 Temperature and Humidity Data Logging
Featured Products

74 Sensor Communications Interface
Featured Products

77 Recommended Solutions

Environmental Automation

83 Overview

85 Elements of Environmental Automation Systems
Featured Products

95 Building Energy Measurement and Management
Featured Products

102 Control Systems
Featured Products

109 Recommended Solutions

Motor Control

117 Overview
Featured Products

130 Recommended Solutions

Calibration and Automated Calibration

139 Recommended Solutions

Legal Notices

143 Trademark Information

Programmable Logic Controllers (PLCs)

Overview

Introduction

Programmable logic controllers (PLCs) have been an integral part of factory automation and industrial process control for decades. PLCs are dedicated computers that have an architecture designed to accommodate control functions. They control a wide array of applications from simple lighting functions to environmental systems to complete chemical processing plants. These systems perform many functions, providing a variety of analog and digital input and output interfaces, signal processing, data conversion, and various communications protocols.

The architecture of a PLC must be sufficiently flexible and configurable to meet the diverse needs of a wide variety of control applications. Inputs (either analog or digital) are received from human operators, machines, sensors, and process events in the form of voltage or current signals. The PLC must accurately receive and interpret these inputs so they can be presented to the control application running on the PLC, which will then determine a set of outputs. These outputs are sent to control actuators in order to maintain control or to cause desired modifications in the process.

Modern PLCs were introduced in the 1960s, and for decades the general function and signal-path flow changed little. However, 21st century process control is placing new and tougher demands on PLCs: higher performance (higher speed, greater precision), smaller form factor, more functional flexibility, and built-in protection against potentially damaging electrostatic discharge (ESD), electromagnetic interference and radio frequency interference (EMI/RFI), and high-amplitude transient pulses found in the harsh industrial setting.

Today, the PLC role has been expanded to include more targeted PLCs for specific applications. Safety PLCs include extra safety features and redundancy for safety-critical applications. Mini- and micro-PLCs automate simpler systems.

Standard PLCs are also improving and are being integrated with other systems such as programmable automation controllers (PACs). PACs typically add motion control, machine vision, easier programming, more communications functions, etc. Doing so allows the PAC to be used in more complex manufacturing operations, but the boundaries between PACs and PLCs are blurring as PLCs add PAC functionality. Throughout this chapter, PLC will be the generic term used for all types of PLCs and PACs. Maxim's products can be used in all of these systems.

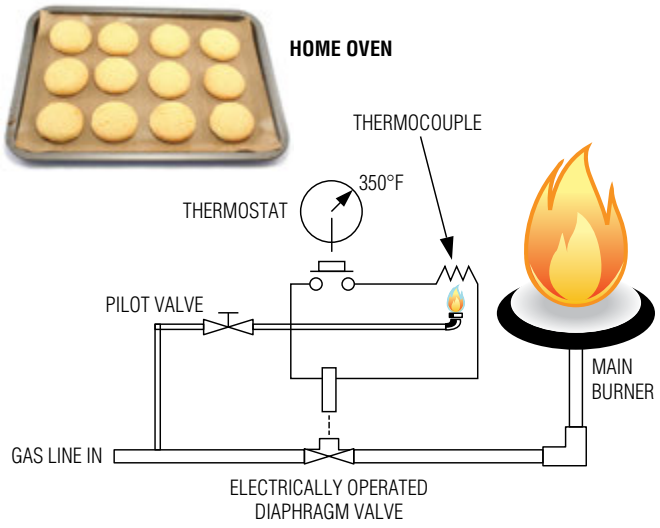
Basic Process Control

How simple can process control be? Consider a common household oven.

The oven's components are enclosed inside one container, so no long distance communication is necessary. When the user sets the thermostat to the desired temperature, the oven maintains the internal temperature at the set point. When the thermostat setting senses that the oven temperature is low, the switch is closed, completing the circuit to open the gas valve to the main burner. Once the thermostat detects that the oven has reached the set point, the switch opens, the gas valve closes, and the main burner shuts off. The cycle repeats as needed. The pilot light provides a fail-safe function while also providing an ignition source for the main burner. If the pilot light were to go out, no voltage would be created by the thermocouple, so the main valve would not open.

Consider a process-control system that goes beyond what is needed for such a small, simple system like a household oven. What controls and configurations are necessary in a factory? For a fully automated bakery, for example, many subsystems are needed such as weigh scales, valves, flow gauges, mixers, yeast-rising warming chambers, ovens, conveyer belts, fans, and packaging equipment. If this bakery is to be fully automated, a process-control system would be needed to manage and coordinate all of the time-critical events between these subsystems.

More complex communications capability is required when the controllers and the controlled elements are separated by a significant distance. In a complex control environment, a PLC spends significant time communicating signals and process events to other components of the system. For more information on communications needs, see the *Fieldbus Functions* section in this chapter.



A household oven serves as a simple example of process control.

PLC Design Goals

Robustness

PLCs are expected to work flawlessly for years in industrial environments that are hazardous to the very microelectronic components that give modern PLCs their excellent flexibility and precision. No mixed-signal IC company understands this better than Maxim. Since our inception, we have led the industry with exceptional product reliability and innovative approaches to protect high-performance electronics from real environmental dangers, including high levels of ESD, large transient voltage swings, and EMI/RFI. Designers have long embraced Maxim's products because they continue to solve difficult analog and mixed-signal design problems.

Higher Integration

PLCs have from four to hundreds of I/O channels in a wide variety of form factors, so size and power can be as important as system accuracy and reliability. Maxim leads the industry in integrating the right features into our ICs, thereby reducing the overall system footprint and power demands and making designs more compact. Maxim has hundreds of low-power, high-precision ICs that come in the smallest available footprints, allowing the system designer to create precision products that meet strict space and power requirements.

Communications

The PLC communicates on two paths. One path is with the process itself, and the other path is with other PLCs in the system and with the human machine interface (HMI), distributed control system (DCS), or supervisory control and data acquisition (SCADA) system. If the PLC is placed so it can communicate directly with the process machines, actuators, or sensors, the interface can be analog, binary (on/off), or digital (1s and 0s). If the interface is analog, the cable length is limited by noise concerns and the risk to signal integrity. These analog interfaces are point-to-point, requiring significant amounts of wiring—one cable for each I/O point. Maxim offers a complete portfolio of analog signal-processing solutions for these sensitive interfaces. For more information on analog signal-processing content, see the *Analog Input Functions* and *Analog Output Functions* sections in this chapter.

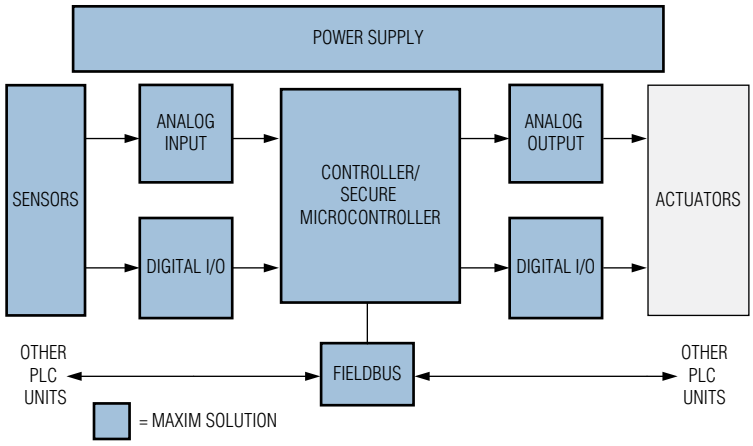
For PLCs at the lowest level in the factory (in the "field"), the communication with other PLCs as well as these PLCs at higher levels in the structure occurs through a digital network called a fieldbus. Some fieldbuses must be deterministic (i.e., meet strict timing requirements), which allows them real-time distributed process control. Other fieldbus protocols are not required to be deterministic. By stringing multiple PLCs along a single fieldbus, fieldbuses significantly reduce wiring needs over point-to-point connections to a higher level PLC in the system. In addition to having multiple PLCs on a single fieldbus, multiple fieldbuses can be bridged to extend them beyond their normal hardware limits.

It is not uncommon for the path to the higher level in the control structure to be through another PLC. That PLC commonly communicates to the HMI, DCS, or SCADA system through the Ethernet (or Industrial Ethernet, if determinism is still required at the higher level). For more information, see the *Fieldbus Functions* section in this chapter.

Computation

Aside from performing the communications functions, PLCs must process inputs from both sides and drive outputs in response. Depending upon the main task of the given PLC, the processing functions may be extensive and time critical, thus demanding sophisticated and fast CPUs. For more information, see the *CPU Functions* section in this chapter.

The architecture of the PLC is modular and can be separated into distinct functions. PLCs are commonly divided into computing modules, I/O modules, and communications modules. The exact content of each of these modules will likely be as diverse as the applications. I/O modules can cover a broad spectrum of signal types. These are often dedicated to a specific application such as a resistance temperature detector (RTD), sensor, or thermocouple sensor. In general, the following capabilities are needed in a PLC: analog input, analog output, digital data communications (e.g., a fieldbus), digital I/O, CPU, and power. We will examine each of these core functions in this chapter; sensors and sensor interfaces are discussed in separate sections within this document.



Simplified PLC block diagram.

www.maxim-ic.com/plc

Analog Input Functions

Overview

The analog input portion of a PLC accepts analog signals from a variety of sensors via factory or field wiring. These sensors are used to convert physical phenomena (such as light, temperature, pressure, proximity, sound, gas, or vibration) into electrical representations. In the analog-input signal path, signals are conditioned for maximum integrity, range, and resolution before being sampled by the analog-to-digital converters (ADCs). The analog input module receives many different signals in the tough industrial environment. It is, therefore, essential to filter out as much of the noise and retain as much of the crucial information as possible when the signals are converted analog to digital.

The PLC's analog input accepts voltage and current inputs from remote sensors. Voltage inputs can have different amplitudes, the most common of which are either 0 to 10V, 0 to 5V, ±10V, or ±5V. The most popular current-input standard is 4–20mA, although ±20mA is sometimes used. Despite its name, the 4–20mA standard accepts 0–24mA both to detect an open input (< 3.6mA) and overrange (> 20mA), and to allow headroom for calibration. To guarantee that the current loop is never broken, the current input typically terminates into a relatively low-value resistor (typically from 25Ω to 250Ω) prior to the signal-conditioning analog chain.

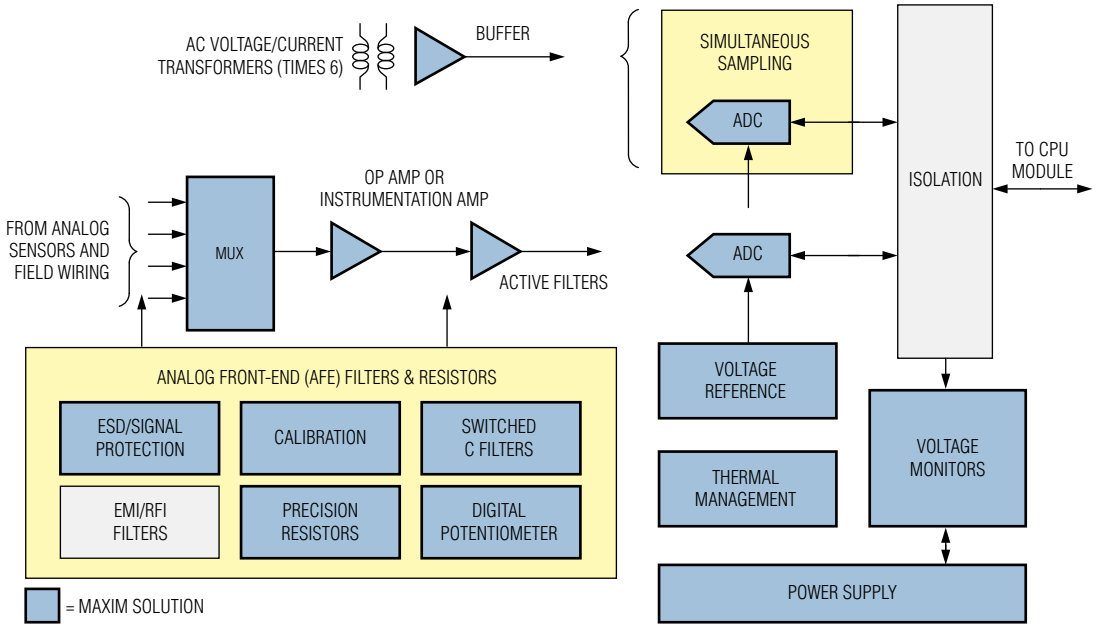
The Signal Chain

Various implementations of the signal chain are possible, with simultaneous-sampling ADCs and independent conditioning amplifiers, or with a mux at the first stage followed by a common amplifying signal path into an ADC, or with individual amplifying channels and a mux prior to the ADC. The input stage is commonly required to cope with both positive and negative high voltages (e.g., ±30V or higher). This protects the PLC's analog-input card from external fault conditions and lets the input module accommodate variable common-mode voltages on the long lines that connect to the remote sensors. Low-temperature drift and low noise are also critical requirements of the analog signal path. Errors at +25°C are typically calibrated in software. Drift over temperature can also be removed, although it is not removed in many systems and thus becomes a critical specification.

Analog-to-Digital Conversion

Standard PLC designs typically require a high-accuracy ADC. The bandwidth of the input signal dictates the ADC's maximum sampling rate. The signal-to-noise ratio (SNR) and spurious-free dynamic range (SFDR) specifications dictate the ADC's resolution, filtering requirements, and gain stages.

It is also important to determine how the ADC will interface to the microcontroller or CPU. For example, high-bandwidth applications perform better using a parallel or fast serial interface. SPI with unidirectional signaling offers easy galvanic isolation to reduce ground loops in the plant. Galvanic isolation can be accomplished via optical, capacitor, or transformer coupling. I^2C's two-line digital interface can also be used, but it is best for slower systems where the PLC's signal is used within a small area and galvanic isolation is not needed since it is difficult to isolate bidirectional lines.



Maxim's extensive product offerings are found throughout this block diagram of PLC analog input functions.

Applications that require extraction of phase information between channels are well suited for multiple ADCs or simultaneous-sampling multichannel ADCs.

Although PLCs are used in distinct ways, many PLC designs share some common factors. For example, ADCs and DACs used in process-control systems range from 10 to 16 bits with 16 bits being one of the most common resolutions. Maxim offers many choices from 10-bit to 24-bit ADCs for a wide range of input voltages. This broad product offering is a distinct advantage for the PLC designer.

For precise systems, ADCs (and DACs) require an accurate voltage reference. The voltage reference can be internal or external to the data converter. In addition to many ADCs and DACs with internal references, Maxim has stand-alone voltage references with temperature coefficients as low as 1ppm/°C, output voltage as accurate as ±0.02%, and output noise as low as 1.3μV_{P-P} that can be used external to the data converter for ultimate precision and accuracy.

The number of data converters can often be kept low by using muxes to choose from several signal sources and programmable gain amps (PGAs) to maximize the ADC dynamic range for each signal. Of course this method does not preserve phase information between the signal sources. When choosing a mux, the sensor's output bandwidth must be considered. The designer needs to determine how often the sensor must be measured. Sensors responding to slowly changing parameters such as temperature and humidity can usually be read every few seconds to capture the needed information, but sensors detecting quickly changing properties like pressure or proximity may need to be measured thousands of times per second.

Signal Conditioning

There are many design challenges when selecting analog-input signal-path components. Input analog signal conditioning could require sensor biasing, converting currents to voltages, selecting from multiple signal sources signal amplification at potentially adjustable gains, and anti-alias filtering. Maxim provides a wide selection of muxes, operational amplifiers, instrumentation amps, PGAs, precision resistor dividers, filters, references, and ADCs to solve these design challenges.

Maxim provides high-precision high-voltage analog front-end operational amplifiers that increases system accuracy and performance. The MAX44251, for example, offers dual-channel precision signal conditioning. Operating from split supplies of either ±5V or ±10V, the MAX44251 offers low-noise performance, 5.9nV/√Hz at 0.1Hz, making it ideal for RTD applications.

Selecting a mux can be an involved process since it is very close to the harsh industrial environment. A mux that meets high ESD ratings or is fault protected against overvoltage can help eliminate expensive external circuitry such as voltage-dividers and opto relays. Low matching on-resistance (R_{ON}) and low-leakage currents are essential for low distortion to improve circuit accuracy and precision by minimizing voltage-measurement errors. Maxim's product portfolio includes ESD-protected, high-voltage-protected, low-leakage, and low-R_{ON} muxes ideal for PLC applications.

The designer will choose the physical position for the signal-conditioning circuitry. That placement may require the sensor signal to be conditioned before it is transmitted to the input ADC.

The sensor's output can be very small or very large, which would require gain or attenuation stages, respectively, to maximize the ADC's dynamic input range. These conditioning stages are usually implemented with PGAs or discrete op amps and precision resistor-dividers. The ADC and amplifiers work in tandem to achieve the best SNR within budgets for cost, power, and size. An alternative is to use an ADC with the conditioning stages integrated. Regardless of how the signal-conditioning stages are implemented, the voltage range, low-temperature drift, and low noise are among the most critical specifications when determining the best architecture.

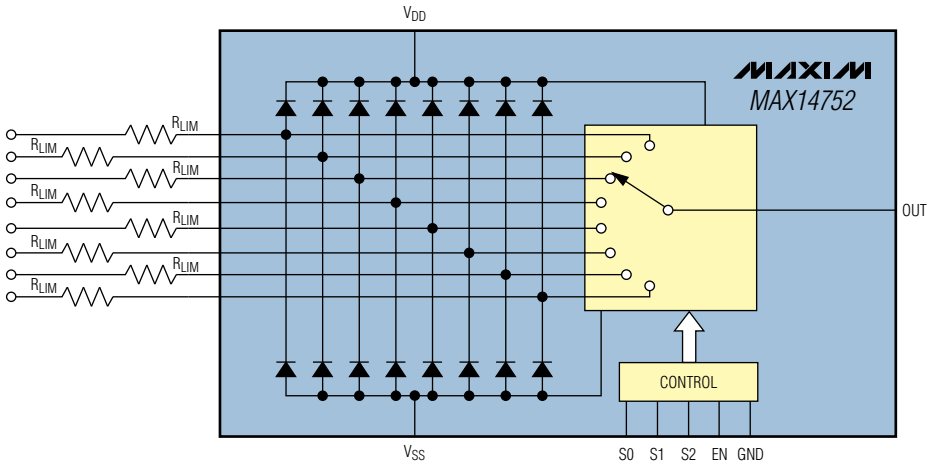
The industrial environment presents numerous noise sources, such as 50Hz/60Hz powerline mains, which get coupled into the signal. These unwanted noise signals put an artificial limit on the gain stages and should be rejected beforehand. This is best accomplished using Maxim's PGAs or differential amplifiers with a high common-mode rejection ratio (CMRR). Maxim has a variety of laser-trimmed, matching resistor-dividers for precise gain and attenuation. There are also trimmable calibration potentiometers for system self-calibration, and ADCs with differential inputs and PGAs integrated in a single IC.

Lowpass or bandpass filtering before the ADC sampling network is necessary for anti-aliasing requirements and for rejecting noise sources at other frequencies. PLC designers have a choice between active filters implemented with op amps or switched-capacitor filters with a very sharp (up to 8-pole) roll-off and a programmable cut-off frequency. Maxim provides a selection of 5th- and 8th-order switched-capacitor and continuous-time filters ideal for anti-aliasing.

Eliminate External Overvoltage Protection (OVP) Circuitry and Reduce BOM Complexity with High-Voltage Multiplexers

MAX14752/MAX14753

The MAX14752/MAX14753 are 8-to-1 and dual 4-to-1, respectively, high-voltage analog multiplexers designed for high-voltage PLC applications. Both devices operate with dual supplies of ±10V to ±36V or a single supply of 20V to 72V, and a low 0.03Ω (typ) R_{ON} flatness. Logic levels for the channel-select interface are defined by the EN input to help interface with multivoltage systems. The MAX14752/MAX14753 are packaged in the standard 16-pin TSSOP, and are pin compatible with the industry-standard MAX308/MAX309 and DG408/DG409. Both multiplexers are specified over the extended -40°C to +85°C operating temperature range.



Input overvoltage and undervoltage clamping with the MAX14752.

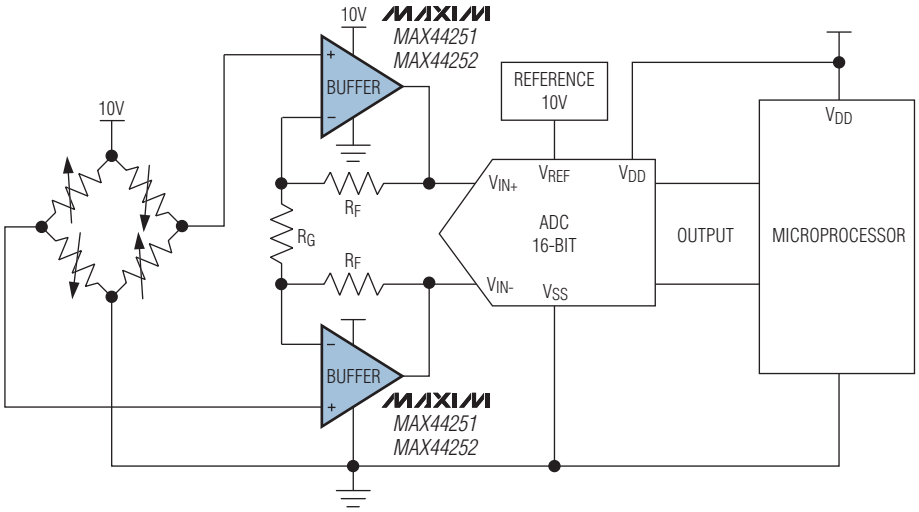
Benefits

- High supply voltage simplifies designs by eliminating external parts
  - Wide, +72V (max) single, power-supply range; dual ±36V (max) power-supply range
  - Internal protection diodes can be used for OVP
  - Rail-to-rail operation allows a large dynamic range
- Excellent R_{ON} flatness for high-accuracy measurements
  - 0.03Ω (typ) R_{ON} flatness over common-mode voltage
- Flexible logic levels for interfacing with multivoltage systems
  - Device enable (EN) defines voltage logic level of channel-select inputs
- Easy upgrade path
  - Pin compatible with industry-standard MAX308/MAX309 and DG408/DG409

Improve Accuracy with Precision Over Time and Precision Over Temperature from Ultra-High-Precision Op Amps

*MAX44251/MAX44252**

The MAX44251/MAX44252 are 20V, ultra-precision, low-noise, low-drift amplifiers that offer near-zero DC offset and drift through the use of patented autocorrelating zeroing techniques. This method constantly measures and compensates the input offset, thereby eliminating drift over time and temperature, and the effect of 1/f noise.



The MAX44251/52 op amps are ideal for driving ADCs.

Benefits

- Maintain system calibration and accuracy over time and temperature with low-temperature coefficients
  - Autozero technology reduces voltage offset temperature coefficient (TCV_{OS}) to 20nV/˚C and V_{OS} to only 6µV (max)
- Improve system accuracy and resolution with low-input voltage noise
  - Having no 1/f component ensures low-distortion signal conditioning below 0.1Hz with 5.9nV input-voltage noise density

*Future product—contact the factory for availability.

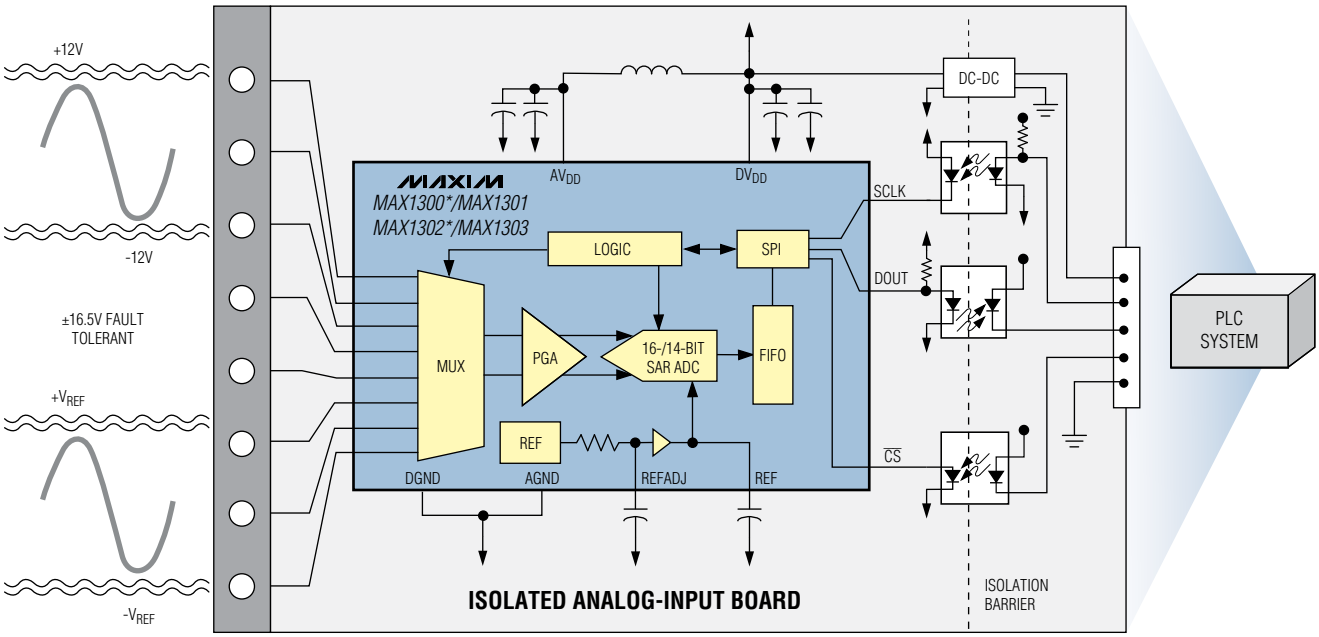
16-Bit ADC with Software-Programmable Input Ranges on Each ADC Channel Saves Design Time

MAX1300/MAX1301, MAX1302*/MAX1303*

The MAX1300/MAX1301/MAX1302/MAX1303 ADC family is an ideal fit for PLC applications because they measure many unique unipolar and bipolar input ranges, all with 16-bit operation and no missing codes. The eight single-ended or differential-input ranges vary as low as a unipolar 0 to 2.048V full scale up to a bipolar ±12.288V full scale. Each input channel can be programmed by software for a different input range, making the MAX1300 family highly versatile. By eliminating analog front-end stages, these ADCs also reduce cost and area, while increasing accuracy. The ADCs are available with 14-bit resolution and 4 or 8 channels.

Benefits

- Reduce complexity and cost by eliminating external gain stages and muxes
  - Each ADC measures eight unique bipolar and unipolar input ranges
  - Multiple software-programmable input ranges up to ±12.288V full scale
- Flexible, easy-to-reuse circuit for multiple applications
  - 16-bit and 14-bit resolution in the same package
- Eliminate external protection components and save space and cost
  - Up to ±16.5V analog-input protection



The MAX1300–MAX1303 ADCs reduce cost by offering programmable input-voltage ranges.

*Future product—contact the factory for availability.

24-Bit ADC Offers the Highest Resolution for 4–20mA Loops

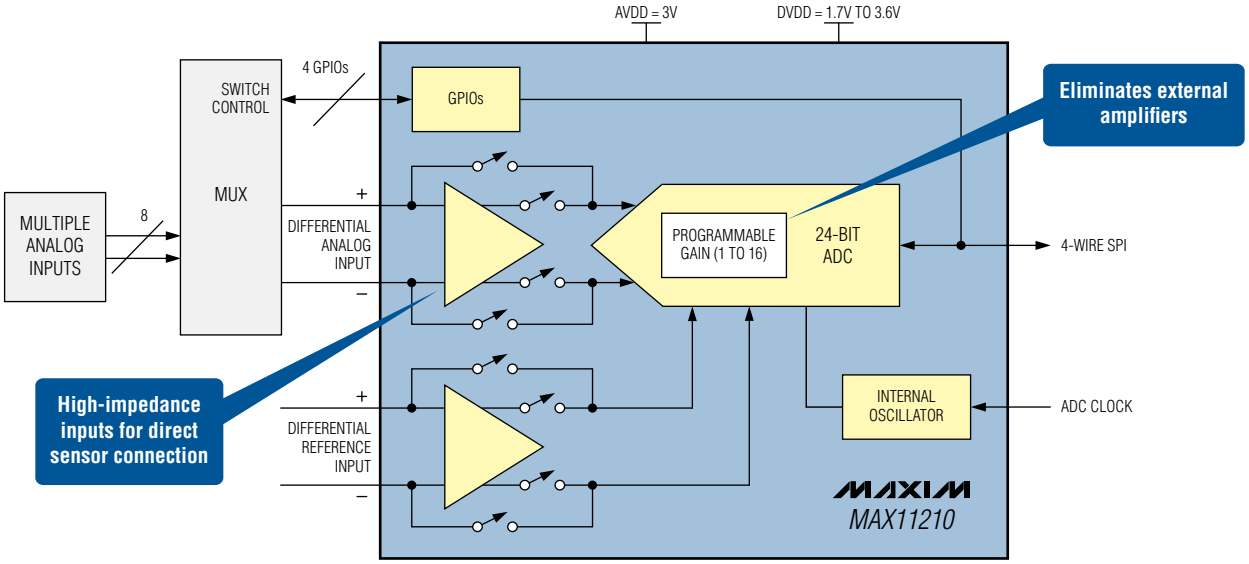
MAX11210

The MAX11210 24-bit, 1-channel ADC offers an industry-leading 23.9 bits effective resolution at < 300µA (max) supply current. The MAX11210's higher effective resolution eliminates power-hungry gain stages while achieving the highest precision possible from the sensor. Applications such as 4–20mA loop sensors put a premium on power dissipation. ADCs are given a maximum power budget of 500µA to resolve minute changes from sensors that measure signals such as temperature, pressure, and flow rate.

The MAX11210 reduces power, cost, and size in two unique ways, offering four general-purpose input/output (GPIO) lines, and integrating buffer amplifiers on the analog and reference inputs. The four GPIO lines can be used to control an external 16-channel multiplexer, effectively converting the MAX11210 into a 16-channel ADC. Bringing the mux control local to the ADC eliminates up to four digital isolators. Isolation is required to achieve the best performance from an ultra-low noise system.

Benefits

- Offers highest resolution for low-power 4–20mA applications
  - 23.9-bit effective resolution
  - 230µA active current, 0.4µA sleep current
- Allows reduced board size due to highly integrated functionality in small package
  - No external buffers or amplifiers needed
  - µMAX® packages as small as 15mm^2



The MAX11210 reduces system cost and size by integrating the input and reference buffers.

Analog Output Functions

Overview

Analog output signals are required in situations where a compatible transducer or instrument needs to be driven. Common examples include proportional valves and current-loop-controlled actuators. It can be part of a simple open-loop control system or part of a complex control loop in a proportional-integral-derivative (PID) system where the result of this output is sensed and fed back to the PLC for PID processing.

The Signal Chain

The analog output begins with digital data from the microprocessor. This digital data is converted into an analog voltage or current signal with a digital-to-analog converter (DAC). Signal-conditioning circuitry then provides reconstruction filtering, offset, gain, muxing, sample/hold, and drive amplification as needed.

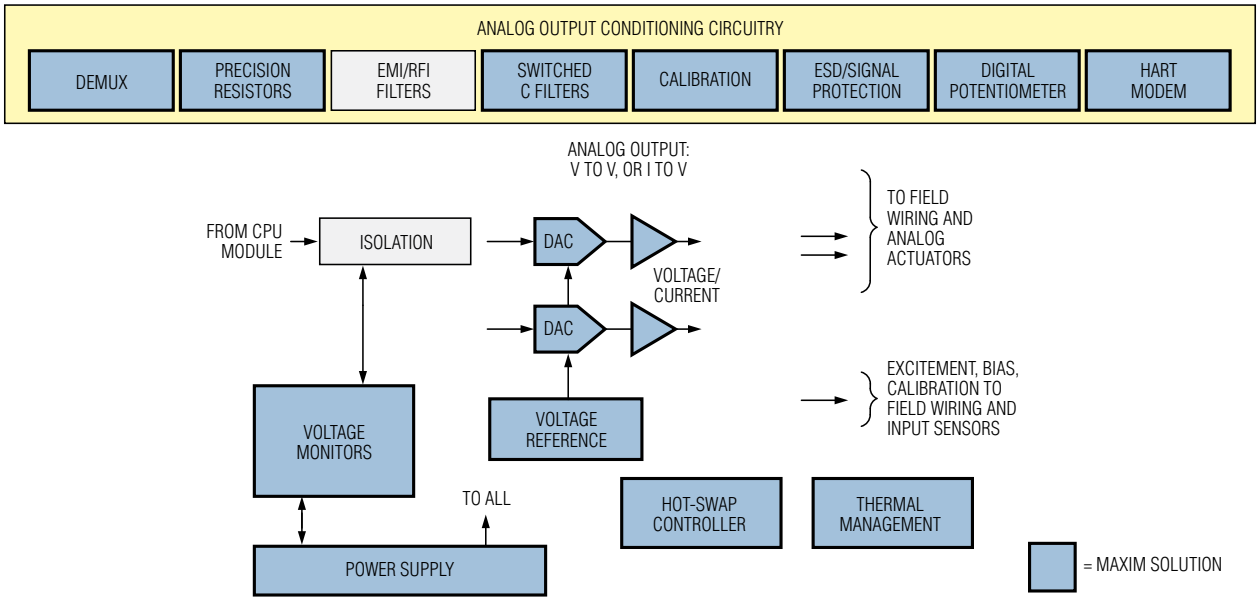
As with the analog inputs, various implementations of the signal chain are possible when multiple analog outputs are needed. Maxim has precision DACs ranging from below 8 bits up to 16 bits of resolution and from a single channel up to 32 channels. Calibration DACs are available from 4 to 16 bits and our sample/hold amplifiers provide additional ways to hold many outputs at constant voltages while the DAC services other outputs. Many of our multichannel DACs allow all outputs to be updated simultaneously through the use of cascaded registers. Maxim's broad product offering is a distinct advantage for the PLC designer.

For precise systems, DACs (and ADCs) require an accurate voltage reference. The voltage reference may be internal or external to the data converter. In addition to many ADCs and DACs with internal references, Maxim has stand-alone voltage references with temperature coefficients as low as 1ppm/°C, output voltage as accurate as ±0.02%, and output noise as low as 1.3μV_{P-P} that can be used external to the data converter for ultimate precision and accuracy.

Producing discrete, selectable, voltage-output (bipolar and unipolar), or current-output conditioning circuits can be an involved task. This is especially true as one begins to understand the necessity of controlling full-scale gain variations, the multiple reset levels for bipolar and unipolar voltages, or the different output-current levels that may be needed to provide the PLC with the most flexible outputs.

Long-Range Analog Communications

The complex impedance of long cables, EMI, and RFI make voltage-mode control impractical for many long distance runs. Coaxial cables ease some of these problems, but with high cost per foot. Cable impedance degrades voltage waveforms, often requiring preemphasis and signal amplification before transmission. Furthermore, in any voltage signaling system, the danger of sparking is real, especially when connections are made or broken. For hazardous environments sparking must be strictly avoided; instead, a current-control loop is a simple but elegant solution. With this approach wire resistance is removed from the equation because Kirchhoff's law tells us that the current is equal at all points in the loop. Because the loop impedance and bandwidth are low (a few hundred ohms and < 100Hz), EMI and RFI spurious pickup issues are minimized. Current-control loops evolved from early 20th-century teletype impact printers, first as 0–60mA loops and later as 0–20mA loops, where signaling was digital serial with current either on or off indicating 0 or 1, respectively. Advances in PLC systems added 4–20mA



Maxim's product offerings are found throughout this block diagram of PLC analog output functions.

loops, where signaling is analog using any current within the loop range.

Practical loop lengths can be up to tens of kilometers. The only caveat is that the resistance of the loop should not cause the transmitter to run out of voltage while working to maintain the proper current.

For many sensors, the current provides all the operating power needed.

Any measured current-flow level indicates information just as an analog voltage can indicate information. In practice, the 4–20mA current loops operate from a 0 to 24mA current range. However, the current ranges from 0 to 4mA and 20mA to 24mA are used for diagnostics and system calibration. Readings between 0 and 4mA could, for example, indicate a broken wire in the system, and similarly, a current level between 20mA to 24mA could indicate a potential short circuit in the system.

An enhancement for 4–20mA communications is the Highway Addressable Remote Transducer (HART®) protocol, which is backward compatible with 4–20mA instrumentation. HART allows bidirectional, half-duplex communications with microprocessor-based, intelligent field devices. The HART protocol allows digital information to be carried on the same pair of wires with the 4–20mA loop.

Maxim has introduced several devices, including the MAX15500, MAX5661, and DS8500, which greatly simplify the design of 4–20mA loop interfaces in PLC systems.

Signal Protection

The analog output circuitry is connected to wiring, long and short in the field or factory, so the output module must protect the system from ESD, RFI, and EMI. Voltage outputs tend to be appropriate for short-distance transmission wiring; current outputs are commonly used on long cables to reduce EMI from sources like arcing switches and motors.

Signal Monitoring

Output signal-monitoring functions, including detection and reporting of intermittent wire faults, are important safety considerations. Cabling in field or factories is subject to movement and vibration which, in time, can cause wires to open or short to other conductors. Equipment and personnel must remain safe, which necessitates careful monitoring. As a cable is failing, there is usually a period of intermittent operation prior to complete failure. During the intermittent phase, a product with output conditioning capability, such as Maxim's MAX15500 or MAX5661, can detect the failure before it is completed. As an important part of preventive maintenance, this failure detection improves safety and helps to minimize any plant downtime.

Because EMI, RFI, and power-surge conditions can be extreme in a factory, any monitoring must be reliable and not subject to nuisance tripping. Error reporting must be robust so, in practice, reporting is done by establishing minimum timeout periods for detecting and reporting errors. A large noise pulse can look like a momentary cable interruption, but a mechanical cable interruption tends to last longer than a noise pulse. This noise interruption can occur when a large motor is turned on or off and capacitive or inductive coupling occurs between its cabling and other cables in close proximity. Consequently, waiting for a short time (a fraction of a second) allows the fault detector to distinguish between a real cable intermittent fault and a noise pulse.

Extra safety is provided if more conditions than just cable health are monitored. Cable drivers under normal conditions operate within defined temperature rise limits, but shorts on long, higher resistance cables may still allow the driver to generate the voltage needed, thus avoiding a voltage fault detection, but at the expense of higher power dissipation. Thus, output driver chip-temperature detection is needed. Compounding this problem is the wide range of temperatures over which industrial equipment must operate. Ambient temperature sensing and temperature rise of output drivers are both often needed.

The field or factory can be spread over several acres, so monitoring power-supply voltage drops or brownout is also important for system reliability. Output drivers must have enough headroom to fully enhance their internal transistors to avoid excessive power dissipation even with normal loads.

Managing an Output Fault

If an output fault occurs, errors must be latched and presented to a hardware interrupt pin. This gives the system microprocessor time to react to short duration cable outages. By definition, intermittent cable faults will be asynchronous and many will occur while the processor is busy. An interrupt is generated so the processor can then poll the output device registers for the exact condition and respond accordingly.

The output to the field or factory needs to be protected against common wiring errors and shorts. Some faults cannot be tolerated, such as a direct lightning hit. However, the outputs should withstand reasonable fault voltages. The most common errors are shorts to ground or to the 24V power supply, and these errors should be tolerated without the need to replace components.

Managing System Functions

Some sensors require excitation to function, and an output module supplies such signals. Typical examples are an AC signal for capacitive and variable reluctance sensors or a DC signal for a simple LED in a backlit switch.

The analog output can also provide other system-management functions such as monitoring the local isolated power supply, board temperature, or calibration.

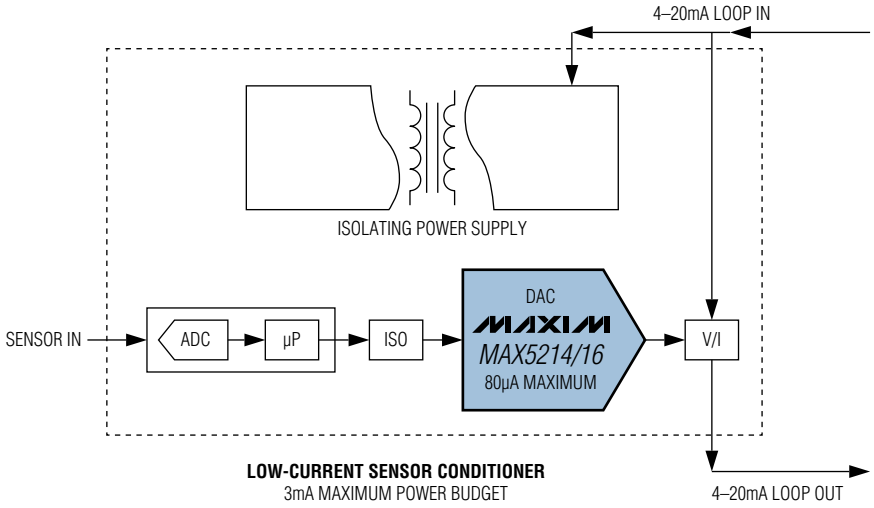
DACs Ideal for Loop-Powered Applications Without Sacrificing Precision and Accuracy for Low Power

MAX5214/MAX5216

The MAX5214/MAX5216 are pin-compatible, 14-bit and 16-bit single-channel, low-power, buffered voltage-output DACs. Power consumption is extremely low in order to accommodate low-power and low-voltage applications, yet the parts accept a wide 2.7V to 5.25V supply voltage range. The DAC output is buffered, resulting in a low supply current of 80µA (max) and a low offset error of ±0.25mV. These devices feature a 3-wire SPI-/QSPI™-/MICROWIRE®-/DSP-compatible serial interface to save board space and to reduce the complexity in isolated applications. A precision external reference is applied through the high resistance input for rail-to-rail operation and low system power consumption. Digital noise feedthrough is minimized by powering down the SCLK and DIN buffers after completion of each serial input frame. On power-up, the DAC output is reset to zero, providing additional safety for applications that drive valves or other transducers that need to be off during power-up. In addition, a zero level applied to the active-low CLR pin asynchronously clears the contents of the input and DAC registers and sets the DAC output to zero independent of the serial interface. The MAX5214/MAX5216 are available in an ultra-small (3mm x 5mm), 8-pin µMAX package, and are specified over the -40°C to +105°C extended industrial temperature range.

Benefits

- Ideal for loop-powered applications
  - Low-power consumption (80µA max)
- Small size and integrated features save PCB area
  - 14-/16-bit resolution in a 3mm x 5mm, 8-pin µMAX package
- Enables high-accuracy performance in industrial environments
  - ±0.25 LSB INL (MAX5214, 14-bit)
  - ±1 LSB INL (MAX5216, 16-bit)
  - Guaranteed monotonic over the operating range
  - Low gain and offset error



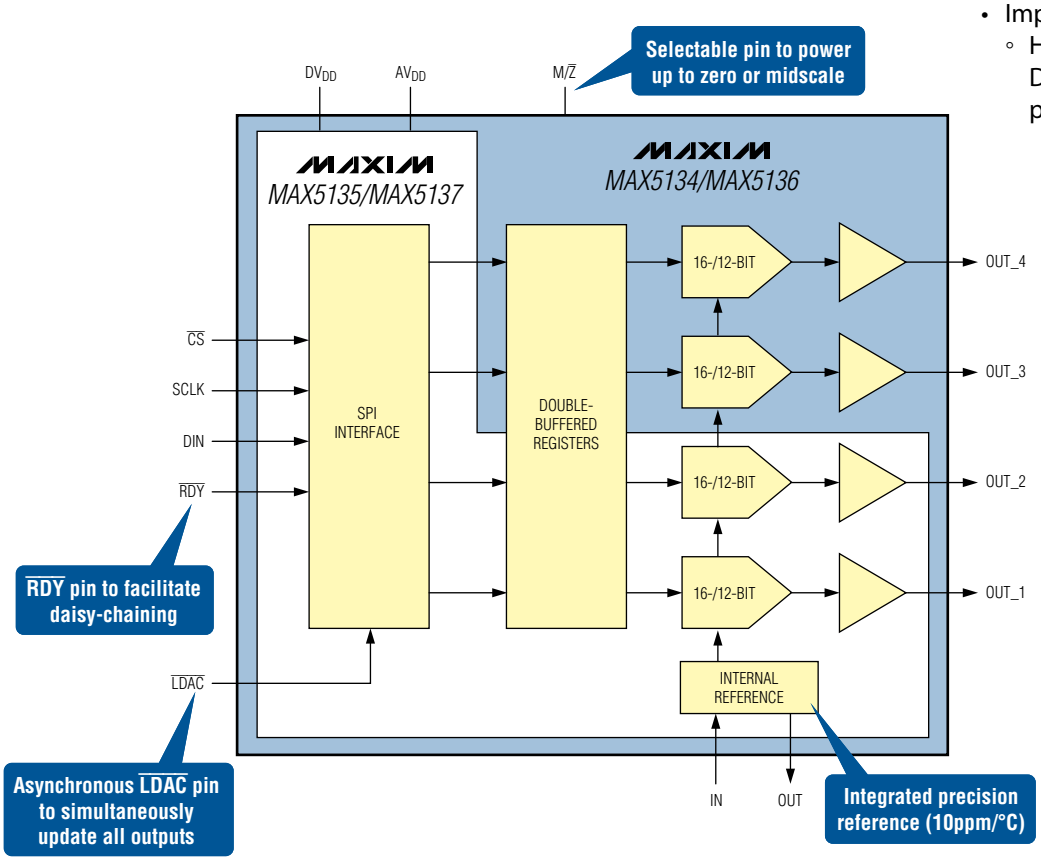
System Flexibility and Reduced Cost with Multichannel DACs

MAX5134/MAX5135/MAX5136/MAX5137

The MAX5134–MAX5137 are pin- and software-compatible 16-bit and 12-bit DACs offering low power, buffered voltage output, and high linearity. They use a precision internal reference or a precision external reference for rail-to-rail operation. The MAX5134–MAX5137 accept a wide 2.7V to 5.25V supply voltage range to accommodate most low-power and low-voltage applications.

Benefits

- Flexible upgrade path
  - 2-/4-channel, 16-/12-bit DACs are pin and software compatible
- Save cost and board space
  - Parts accept an SPI-/QSPI-/MICROWIRE-/DSP-compatible serial interface
  - 4mm x 4mm package
  - A READY output enables easy daisy-chaining of several MAX5134–MAX5137 and other compatible devices
  - Double-buffered hardware and software $\overline{\text{LDAC}}$ provides simultaneous output updates
- Improve safety
  - Hardware input for resetting the DAC outputs to zero or midscale on power-up or reset



Block diagram of the MAX5134–MAX5137 DACs.

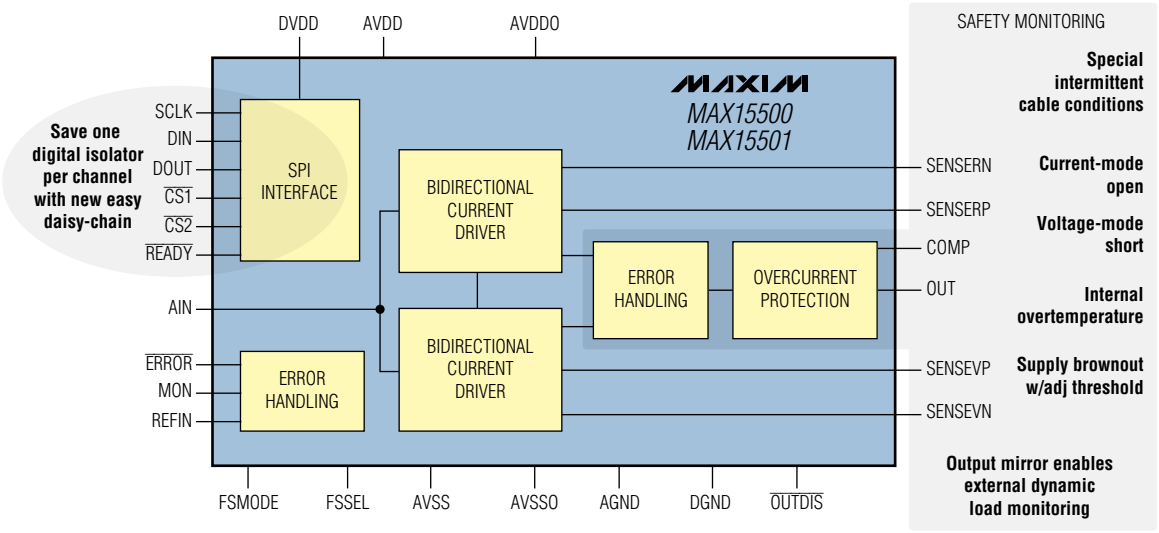
Enhance System Safety and Reliability with an Output Conditioner

MAX15500/MAX15501

The MAX15500/MAX15501 analog output conditioners provide a programmable current up to ±24mA, or a voltage up to ±12V proportional to a control voltage signal. The control voltage is typically supplied by an external DAC with an output voltage range of 0 to 4.096V (MAX15500) and 0 to 2.5V (MAX15501). The output current and voltage are selectable as either unipolar or bipolar. The MAX15500/MAX15501 are programmed through an SPI interface capable of daisy-chained operation.

Benefits

- Enhance robustness
  - Outputs are protected against overcurrent conditions
  - Outputs are protected against a short to ground or supply voltages up to ±35V
- Provide high flexibility and improved diagnostics to enhance reliability
  - Output current and voltage are selectable as unipolar or bipolar
  - Monitor for overtemperature and supply brownout conditions with programmable threshold
  - Extensive error reporting through the SPI interface and an additional open-drain interrupt output
  - Analog output to monitor load conditions



Block diagram of the MAX15500/MAX15501.

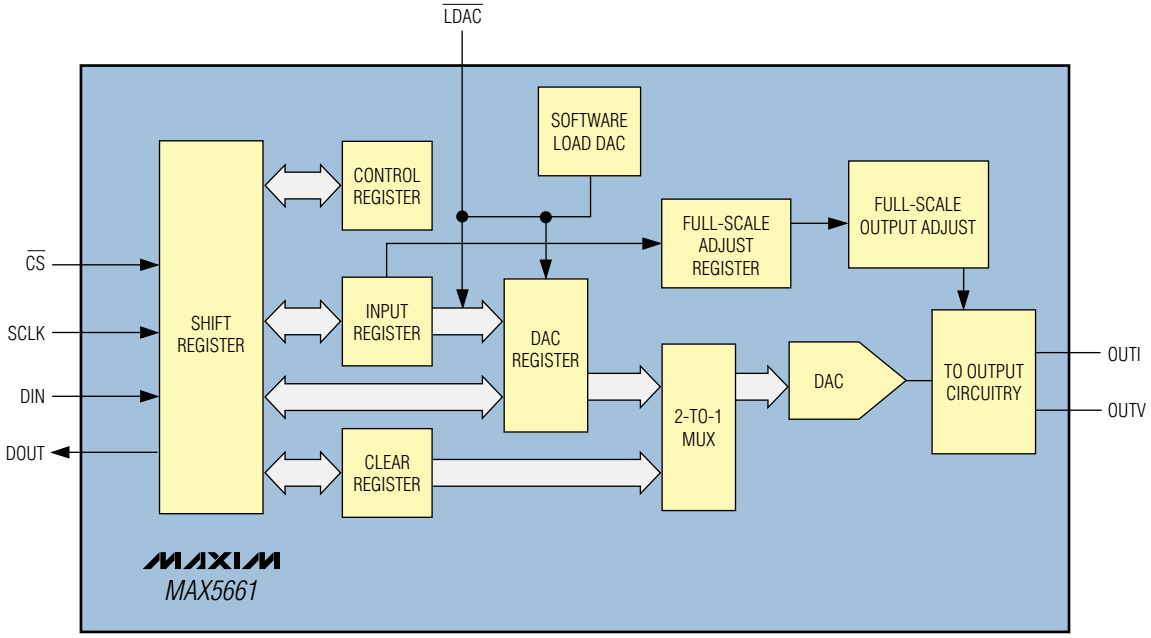
16-Bit DAC with Integrated Voltage and Current Output Conditioner Reduces Board Area and Eliminates External Components

MAX5661

The MAX5661 controls output voltage, output current, and output gain adjustments. This device reduces any challenges that designers face when laying out their analog and mixed-signal boards.

Benefits

- Simplifies board design
  - Software-selectable voltage output or current output
- Eliminates external components
  - Integrated output buffer
  - No additional discrete components required for switching between output modes
- Improves system reliability
  - Supports analog power supplies up to 37.5V



A simplified block diagram of the MAX5661.

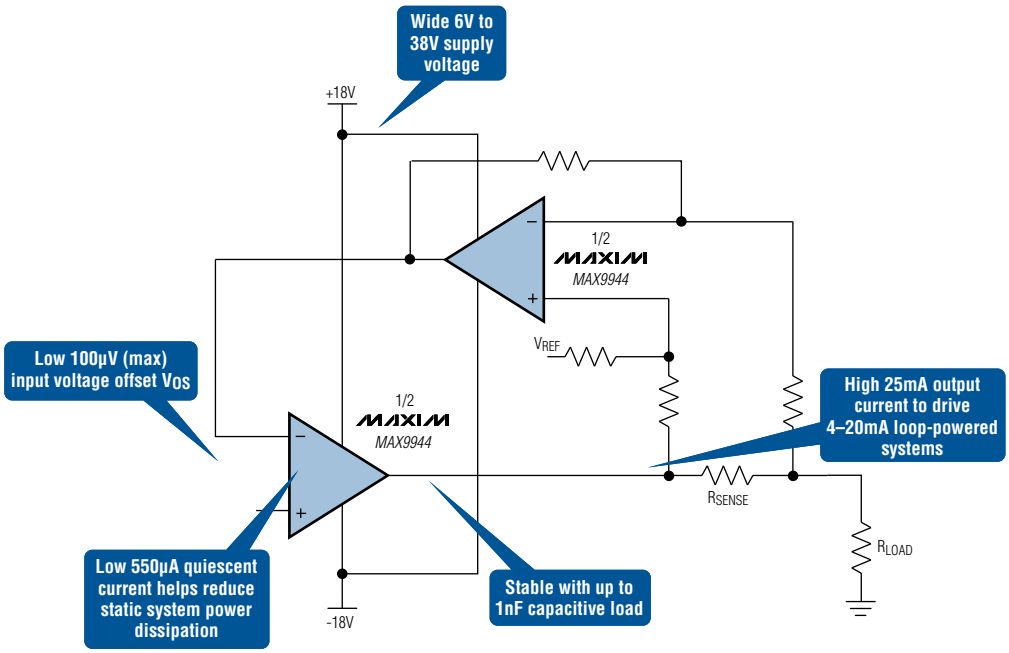
Improve System Accuracy for High-Voltage Applications in a Harsh Environment with High-Precision Output Conditioners and Drivers

MAX9943/MAX9944

The MAX9943/MAX9944 are high-voltage amplifiers (6V to 38V) that offer precision (100µV_{OS}), low drift (0.4µV/°C), and low 550µA power consumption. The devices are ideal for sensor signal conditioning, high-performance industrial instrumentation, and loop-powered systems (e.g., 4–20mA transmitters).

Benefits

- Easily drives 24V biased 4–20mA lines throughout factory floors
  - High supply-voltage operation and high-output drive exceed current-mode communication requirements

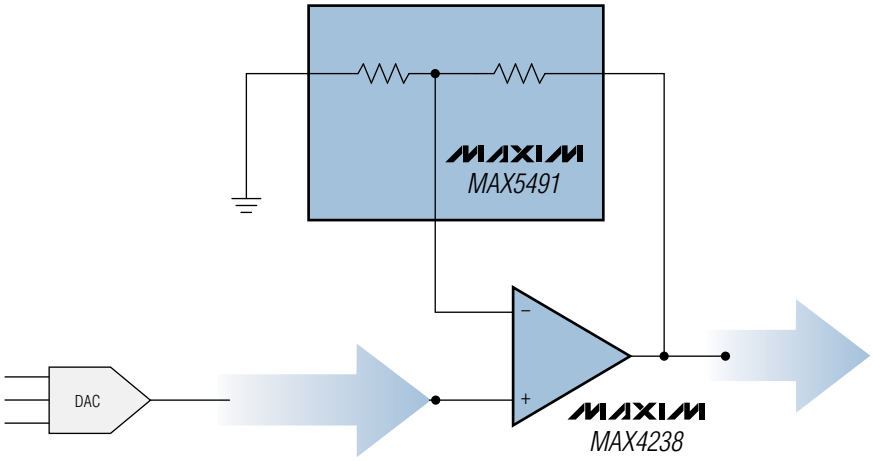


The MAX9944 accurately drives loads.

Resistor Network Saves Cost and Space Without Sacrificing System Precision

MAX5490, MAX5491, MAX5492

The MAX5490 family of precision resistor-dividers consists of two accurately matched resistors with access to the ends and center of the divider. This family offers excellent resistance matching of 0.035% (A grade), 0.05% (B grade), and 0.1% (C grade); includes an extremely low resistance-ratio temperature drift of 2ppm/°C over -40°C to +85°C; and has an end-to-end resistance of 30kΩ. Resistance ratios from 1:1 to 30:1 are available, as are 10 standard ratios.



Implementing a robust, precision analog output with the MAX5491.

Benefits

- Inexpensive and easy to use
  - Up to 80V operating voltage across sum of R1 and R2
  - Resistance ratios from 1:1 to 30:1
  - Tight initial ratio accuracy
  - Three grades: 0.035%, 0.05%, and 0.1%
  - Low 2ppm/°C resistor-ratio-drift
- Save board space
  - Tiny 3-pin SOT23 package

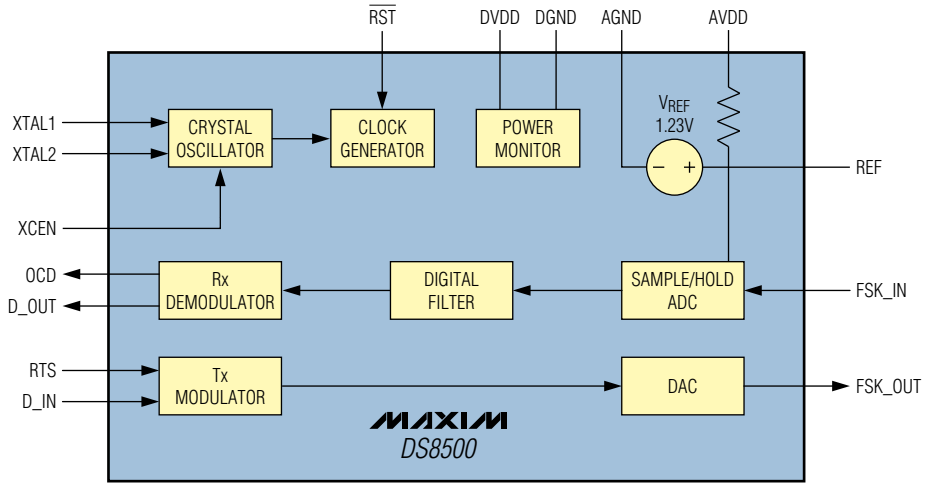
Save Space in Low-Power Process-Control Equipment with a Single-Chip HART Modem

DS8500

The DS8500 is a single-chip modem with HART capabilities that satisfy the HART physical-layer requirements. This device operates in half-duplex fashion, and integrates the modulation and demodulation of the 1200Hz/2200Hz FSK signal while consuming very low power. It only needs a few external components because of the integrated digital-signal processing.

Benefits

- Highly integrated HART modem solution saves space
  - Fewest external components due to the built-in digital-receive filter
  - 5mm x 5mm x 0.8mm, 20-pin TQFN package
- Robust signaling reduces data errors due to lowest harmonic distortion
  - Sinusoidal output signal



Block diagram of the DS8500.

Digital I/O Functions

Overview

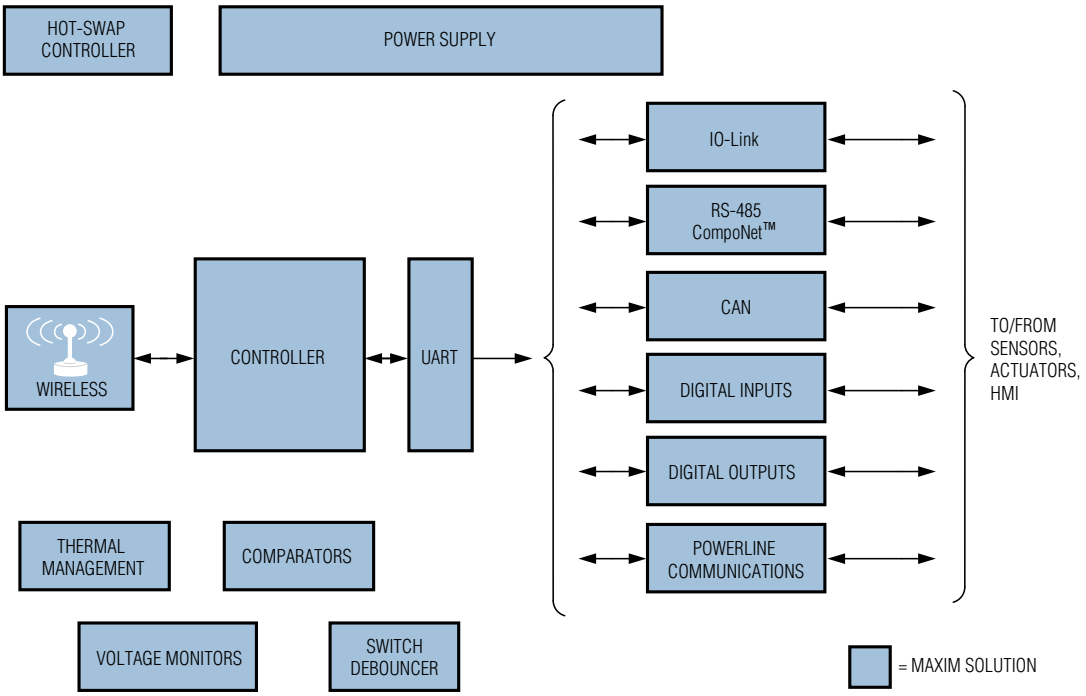
Digital I/Os communicate digitally to industrial sensors and actuators. The sensors and actuators are located in the field and, thus, are represented on the lowest level of the control system's hierarchy. In contrast to analog I/O modules, digital I/O modules send or receive information that is either 1-bit (binary) information or quantized values. The information flow can be unidirectional or bidirectional, depending on the interface type.

The most significant advantage to using digitized information is its tolerance of noise. Consequently, digital I/O functions allow longer cable runs than analog signal cables.

Interface Types

Common digital interfaces are 24V digital I/Os, which are traditionally unidirectional and based on two-, three-, or four-wire cabling. A 24V digital I/O provides both the 24V and ground supplies to the sensor/actuator, as well as one or two (unidirectional) data lines.

IO-Link® is a newer sensor/actuator interface technology based on 24V I/Os. In an IO-Link system, the data line is bidirectional and supports data rates up to 230kbps. The IO-Link point-to-point interface connects one sensor or actuator to one digital I/O port. With intelligent and configurable sensors, IO-Link enables remote configuration, diagnostics, and monitoring of the peripheral equipment.



With an industrial digital I/O interface, 1-bit or quantized data flow to and from the sensors and actuators is easy.

IO-Link Master Transceiver Enables High-Density IO-Link Masters

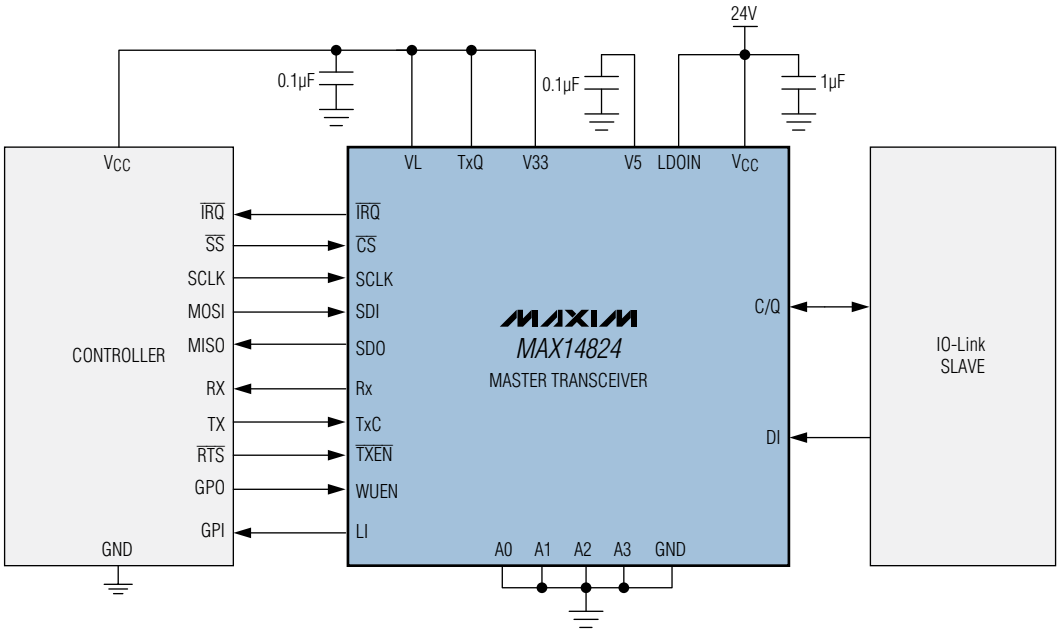
MAX14824

The MAX14824 is an IO-Link master transceiver designed for high-channel-count IO-Link port-count applications. The MAX14824 integrates an IO-Link physical interface with an additional digital input and two regulators. A high-speed 12MHz SPI interface allows fast programming and monitoring of the IO-Link interface. A device or slave transceiver is located in the sensor/actuator module. Maxim also offers IO-Link device transceivers, MAX14820 and MAX14821 (see the *Sensors* chapter), which marry well with the MAX14824.

The MAX14824's in-band addressing and selectable SPI addresses enable multiple devices to be cascaded. The device supports the standard IO-Link data rates and features slew-rate selection to reduce EMI. The driver is guaranteed to drive up to 300mA (min) load currents. Internal wake-up circuitry automatically determines the correct wake-up polarity, thus allowing the use of simple UARTs for wake-up pulse generation. The MAX14824 is available in a 4mm x 4mm, 24-pin TQFN and operates over the extended -40°C to +85°C temperature range.

Benefits

- Lowers cost for high-port-count IO-Link systems
  - SPI in-band addressing
- High-power drive allows direct use for digital outputs, which reduces component count
  - 300mA output directly drives high-power actuators
  - Capable of driving up to 1µF capacitive loads
- High integration reduces solution size and load on processor
  - Automatic wake-up generation allows use of simple processors

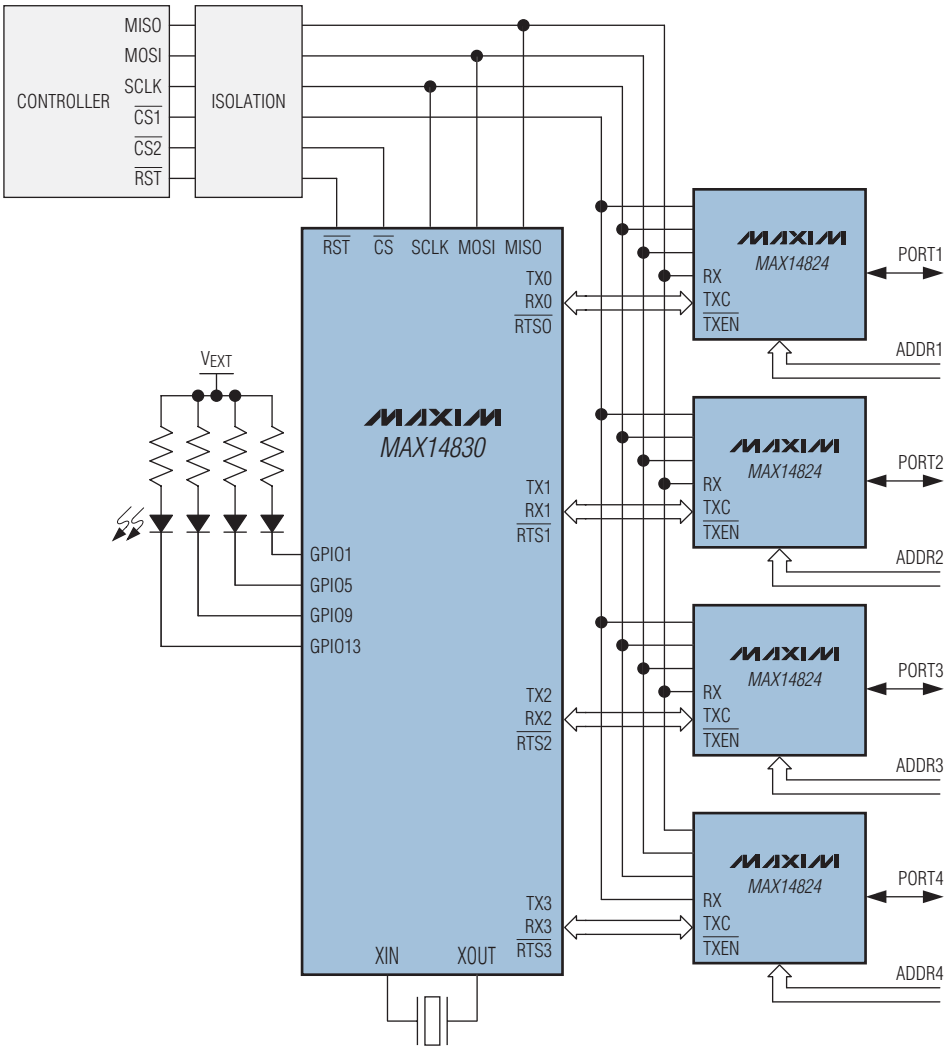


A MAX14824 block diagram of an IO-Link transceiver interfacing to an IO-Link controller to enable 24V, high-speed, bidirectional, digital communication.

Simplest, Most Economical Solution for High-Port-Count IO-Link Systems

MAX14830

The MAX14830 is an advanced quad, serial UART with 128-word FIFOs for high-port-count I/O systems like an IO-Link system. By reducing the number of signals that need be isolated, the serial SPI/I²C host interface is optimized for industrial systems that require galvanic isolation. Many advanced UART and transceiver control features are integrated in the MAX14830 and remove timing-critical tasks from the host controller.



Block diagram of the MAX14830 quad UART.

Benefits

- Handles most low-level transceiver control autonomously, reducing the need for powerful and expensive controllers
  - Automatic hardware and software flow control
  - Automatic transceiver direction control
  - Automatic transmitter disable
- Reduces the need for expensive isolation components, which lowers cost
  - Quad UART combines signals
  - SPI interface has only unidirectional signals, which eases isolation
- Simplified baud-rate generation reduces design time and complexity
  - Integrated PLL, divider, and fractional baud-rate generator
  - Advanced clocking scheme
  - Independent of reference clock
  - Four timers produce programmable clock outputs, which mitigate the need for external clock generators

Fieldbus Functions

Overview

A fieldbus is the communications link between dispersed process-control equipment. The official meaning of fieldbus describes the set of protocols that have been recognized by the Fieldbus Foundation. Distributed control allows local and hierarchical control. There is an important advantage of such a noncentralized control strategy: it avoids high processing power and extensive cabling. Control subsystems can be located close to the sensors and actuators in the field. An example of a fieldbus network application would be along an automobile assembly line, where the fieldbus interconnects controllers located at each assembly stage.

Basic Composition of a Fieldbus

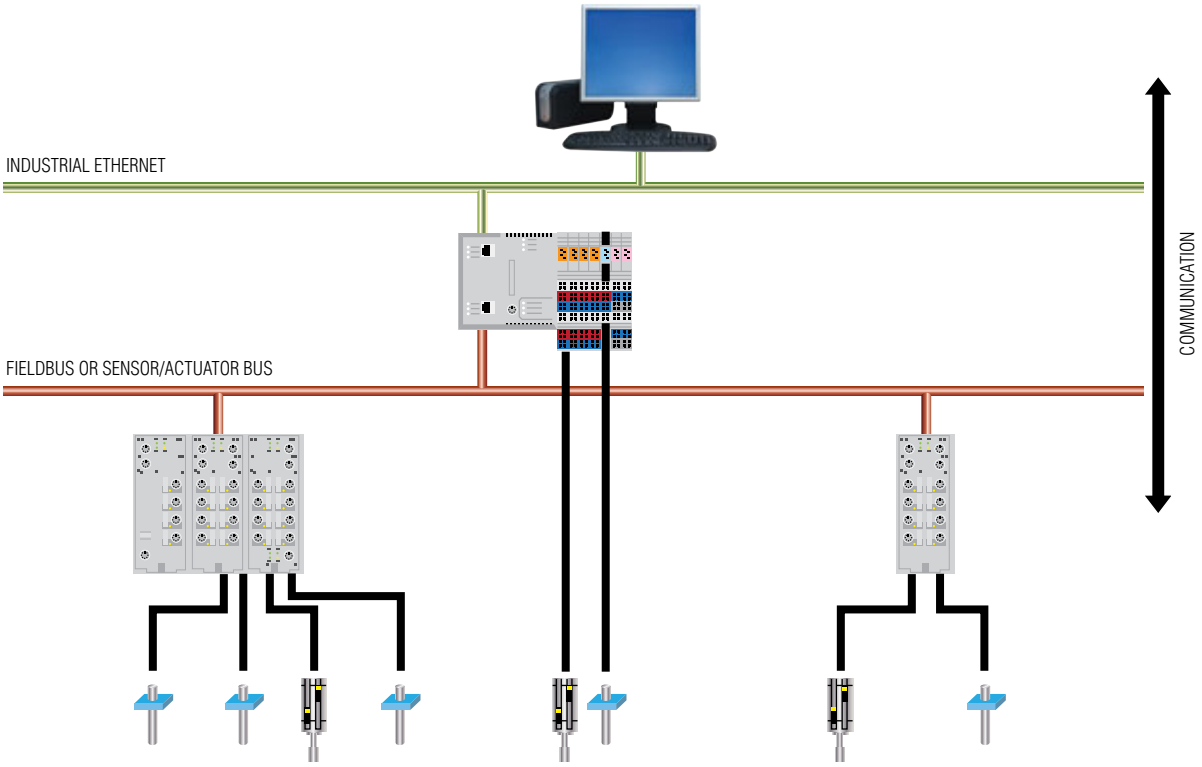
A PLC system has a hierarchical structure in which the upper levels of the fieldbus network use Ethernet-based networking. This hierarchy melds with the other corporate-management IT systems.

Fieldbuses are bidirectional, digital, serial networks. Protocols that have been officially recognized by the Fieldbus Foundation and formalized in IEC 61158 include PROFIBUS, ControlNet, Interbus, and others. PROFIBUS DP (decentralized peripheral) has become one of the most commonly used deterministic fieldbuses for factory automation. PROFIBUS DP is primarily used to network multiple controllers in decentralized locations.

The physical layer of a fieldbus is commonly based on RS-485, CAN, and Ethernet. The fieldbus connects to a PLC subsystem with a fieldbus module, as shown in the figure on the following page.

The fieldbus module bridges the PLC system's backplane protocol to the fieldbus protocol. The backplane, which is common to all modules in the PLC system, can be based on half- or full-duplex RS-485. RS-485 is ideally suited to backplane interconnect in industrial applications because of its high-EMI tolerance, high speed, and hot-plug capability.

Regardless of which fieldbus protocol is used, isolation is required between the PLC and its distributed subsystems

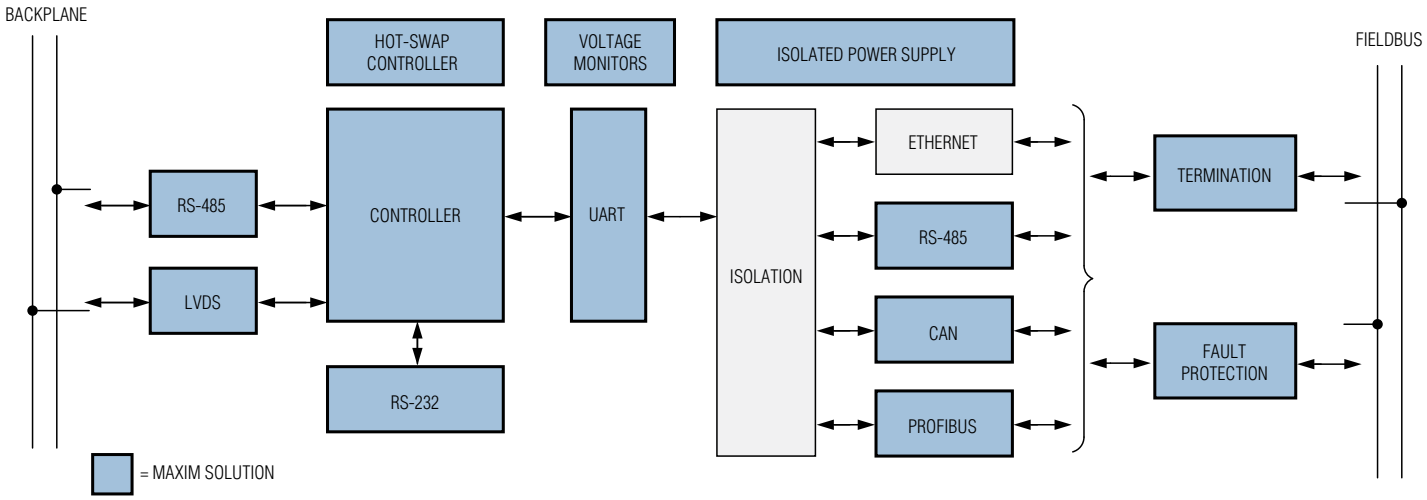


The fieldbus supports communications throughout the factory.

in order to tolerate any ground differences on the factory floor and to protect against any electrical noise on the lines from peripheral sensors.

Harsh conditions typical of industrial applications can make protecting the interface cabling and devices a challenge. It is crucial, therefore, that both the device(s) and system withstand harsh conditions. Only in this way can one ensure that the PLC system's signal integrity and system reliability are maintained. To ensure that the system is protected in harsh industrial environments, PLC designers need to incorporate quite specific safeguards:

- Protection from high ESD: up to ±35kV (HBM) and ±20kV (Air Gap, IEC 61000-4-2)
- Fault protection: tolerance to shorts up to ±80V
- Isolation to allow large common-mode ground differentials
- Line termination to reduce reflections on the cables
- Automotive temperature grade (-40°C to +125°C)



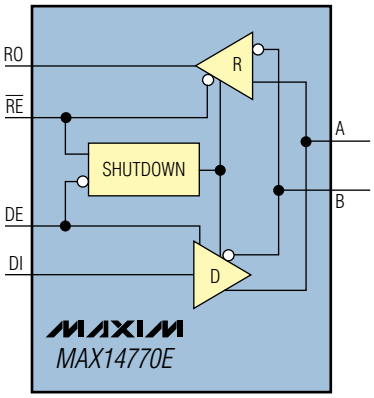
The fieldbus is connected to the PLC backplane by the fieldbus module.

Featured Products

Transceiver Meets PROFIBUS DP Standards and Protects Against ±35kV ESD

MAX14770E

The MAX14770E PROFIBUS DP transceiver meets strict PROFIBUS standards with a high-output-drive differential (greater than 2.1V) and an 8pF bus capacitance. The high-ESD protection (±35kV HBM), high-automotive-temperature grade, and space-saving 8-pin TQFN package make the MAX14770E ideal for space-constrained, harsh industrial environments.



Block diagram of the MAX14770E.

Benefits

- Easy connection to PROFIBUS reduces design time
  - Meets EIA 61158-2 Type 3 PROFIBUS DP specifications
  - -40°C to +125°C temperature range for use in extreme conditions
- Space-saving
  - Tiny 3mm x 3mm, 8-pin TDFN package
- Industry's highest ESD protection enhances reliability
  - ±35kV Human Body Model (HBM)
  - ±20kV IEC 61000-4-2 (Air Gap)
  - ±10kV IEC 61000-4-2 (Contact)

RS-485 Transceivers with Integrated Termination Simplify Equipment Installation

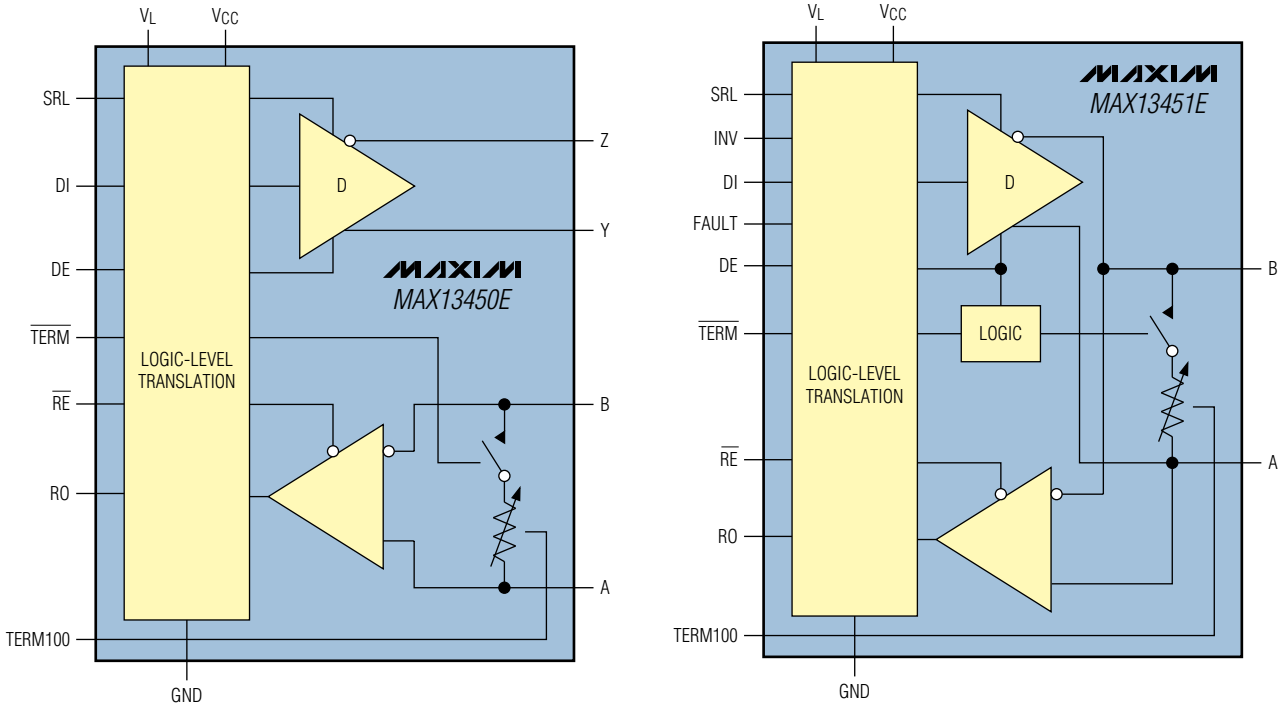
MAX13450E/MAX13451E

RS-485 half-duplex and full-duplex networks operating at high data rates must have their transmission lines terminated at both ends in order to minimize reflections from termination-impedance mismatch. To perform the termination, typically discrete resistors are either put into the equipment or added externally at the end-point devices on the line. Most commonly, 120Ω transmission lines are used in RS-485 applications. Recently, however, 100Ω lines have become preferred because they use Ethernet cables.

The new RS-485 transceivers like the MAX13450E/MAX13451E eliminate the need for external termination resistors because they integrate pin-selectable 100Ω/120Ω resistors. The integrated logic-level translation (V_L pin) provides compatibility with mixed-voltage systems.

Benefits

- Flexible configurations interface to many applications, reducing inventory
  - Pin-selectable 100Ω/120Ω termination resistors eliminate external components
  - Pin-selectable slew-rate limiting improves EMI performance
  - Integrated V_L pin (down to 1.62V) allows interfacing with mixed-voltage systems
- Integrated protection is ideal for harsh environments
  - Fail-safe operation
  - High ±30kV HBM ESD protection
  - Fault output indicates short circuits
- Works over extreme temperatures with safety shutdown
  - -40°C to +125°C automotive temperature grade
  - Thermal shutdown at +150°C



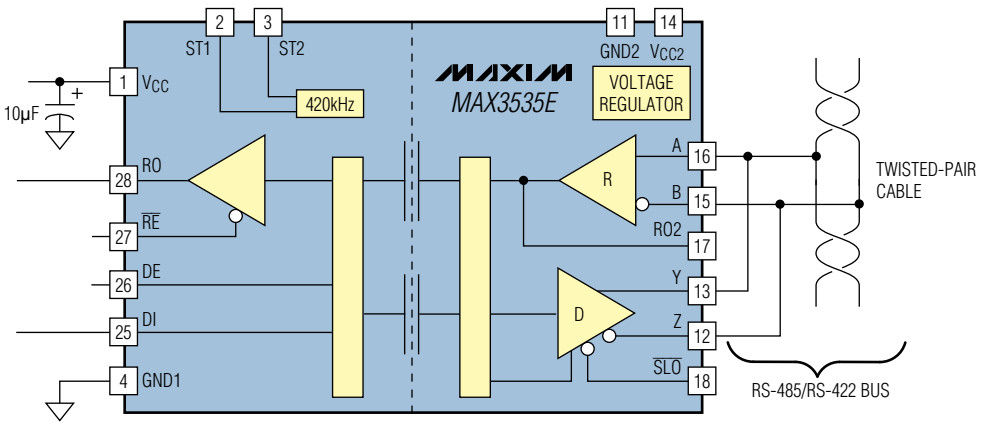
RS-485 transceivers integrate all functions needed for robust industrial communications.

Isolated RS-485 Transceiver Reduces BOM Complexity

MAX3535E

Galvanic isolation between the PLC's backplane and the fieldbus is required due to the harsh conditions and large common-mode voltages that can occur between remotely located subsystems. Maxim offers RS-485 transceivers with integrated isolation based on capacitors, transformers, and optical techniques.

The MAX3535E RS-485 transceiver is designed for applications where galvanic isolation is required up to ±2500V. By integrating the full half-bridge driver and rectifier, the MAX3535E offers ease of use. It provides extended ESD protection up to ±15kV.



Block diagram of the MAX3535E. Dashed line signifies isolation barrier.

Benefits

- Complete isolation solution in one package; saves board space
  - 2500V_{RMS} RS-485 bus isolation using on-chip high-voltage capacitors
- Rugged design protects against ESD strikes and other faults for enhanced reliability
  - Integrated ±15kV HBM ESD
  - Short-circuit protected
  - Fail-safe receiver inputs
- Easy interfacing with multivoltage systems provides design flexibility
  - 3.0V to 5.5V operation
  - Hot-swap-protected driver-enable input

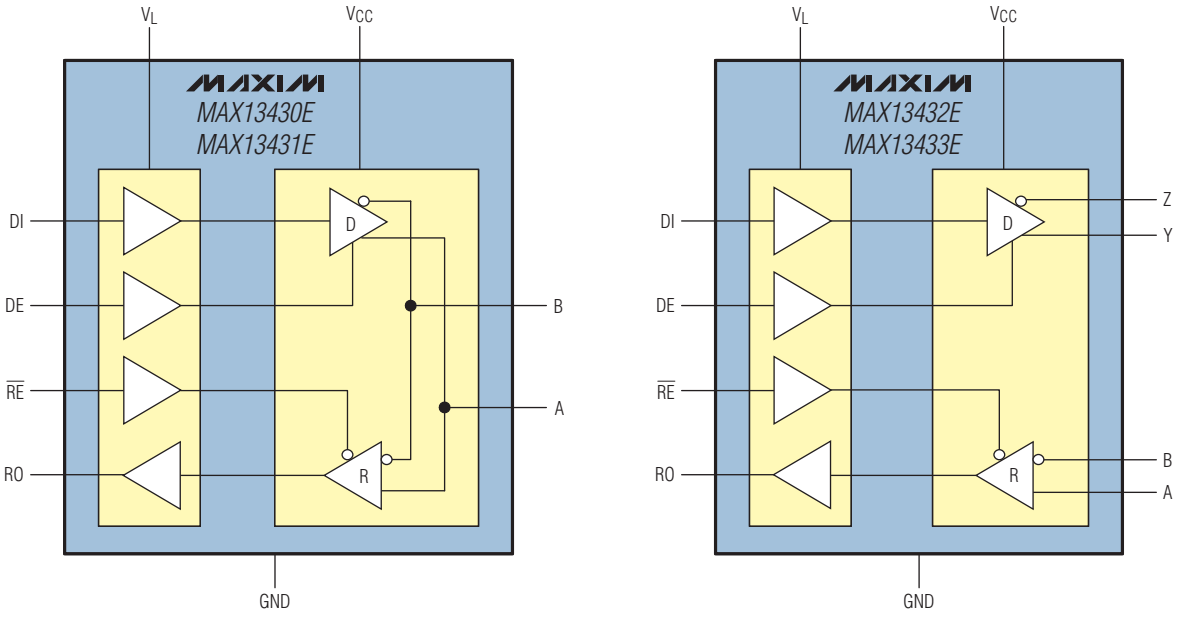
Industry's Smallest RS-485 Transceivers Save Board Space and Reduce BOM Complexity

MAX13430E–MAX13433E

As industrial modules become smaller, pressure mounts for PLC designers to shrink their designs and transition away from the traditional industry-standard packages like SO, SSOP, and PDIP. Maxim offers a full family of RS-485 transceivers available in tiny µMAX/TDFN packages with integrated features that reduce BOM complexity, board space, and cost.

Benefits

- Smallest footprint enables compact designs
  - Available in tiny 10-pin TDFN/µMAX (3mm x 3mm) packages
- Flexible configuration allows design reuse
  - Wide 3V to 5V supply reduces need for 5V supply
  - Integrated V_L pin allows interface with low-voltage logic (down to 1.62V logic) FPGAs and ASICs
  - Enhanced slew-rate limiting facilitates error-free data transmission on improperly terminated lines
- Robust in harsh environments
  - High ±30kV (HBM) ESD provides the industry's most robust ESD protection
  - Hot-swap inputs
  - -40°C to +85°C operation with thermal shutdown protection



Typical operating circuits of the MAX13430E product family.

CPU Functions

Overview

The CPU functions for a PLC include the processor, memory, and support circuitry required to execute the programmed instructions and to communicate with the various I/O functions.

The CPU controls all the PLC activity. The input/output system provides an interface between the CPU and field devices like sensors and switches on the input side and controllable devices like drivers on the output side.

The PLC control program was historically developed in ladder logic, which is a graphical, diagram-based construct used when relays were the primary logic elements controlling an industrial process. But modern development tools allow PLC programmers to use high-level programming environments and to create structured software. If desired, within these sophisticated programming environments PLC programming can still be done using ladder logic.

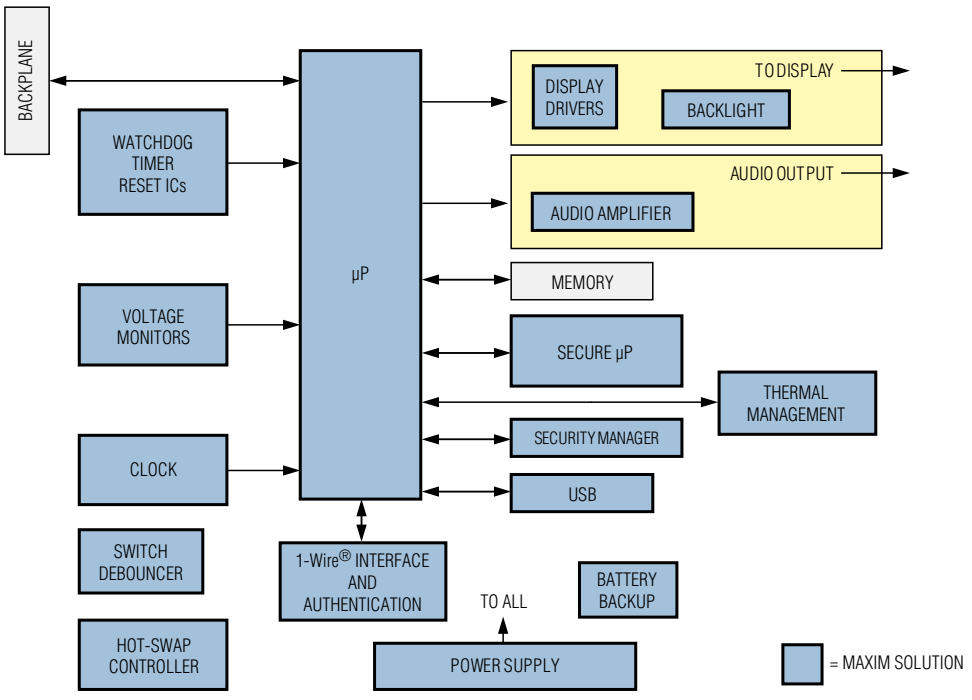
Field devices provide the input data via the input interface to the CPU, which, in a deterministic fashion, executes the control program. Based on the result, the connected controllable devices are adjusted via the output interface, and data is communicated over the communications interface to other PLCs for process coordination and up to the higher levels of the factory process-control system for reporting and data logging. The control process, called scanning, continues until a change has been made to the control program. Many of today's PLC applications require faster scan times that, in turn, depend on a high-performance CPU. The range of PLC types has proliferated: micro-PLCs and mini-PLCs at the low end of CPU performance needs; motion-control PLCs with very fast processing capabilities; and safety-PLCs at the high end of performance capabilities. The safety-PLCs may require CPU redundancy and a host of safety-related features in order to meet safety integrity levels (SILs) in potentially hazardous plan operations.

Self-monitoring functions are performed by the CPU's power-supply voltage monitors, watchdog timers, and reset circuits. Various security functions can be incorporated to ensure the integrity of the CPU's code and its proper execution.

Thermal sensors are used on critical devices and known hot spots where high power dissipation is likely, such as on output drivers or on the CPU.

The CPU module also includes components to enable communications with attached expansion modules, other PLCs, industrial PCs, and the built-in HMI control panel on the PLC. Functions such as switch debounce, display and backlight driving, and audio functions may be needed. Universal asynchronous receiver-transmitters (UARTs) define the fieldbus data rates, ensure data integrity, and interface to either the RS-485 or PROFIBUS transceivers on the fieldbus module.

Isolated power supplies, hot-swap controllers, and battery backup combine for power management on the CPU module.



Block diagram of PLC CPU functions.

Nonisolated and Isolated Power-Supply Functions

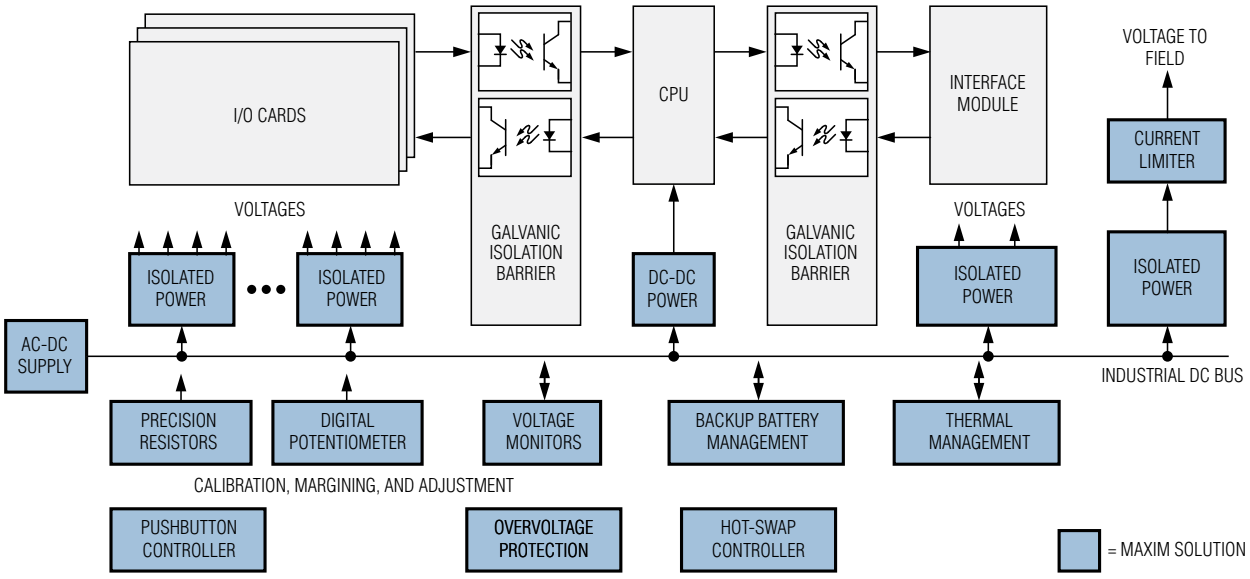
Overview

Typically PLCs have a backplane power rail of +24V DC, although the actual voltage can differ, usually from 12V to 48V. The power comes from an isolated DC-DC converter connected to a factory AC to DC supply. The PLC can be equipped with an auxiliary battery with a special ORing controller. Together, this configuration forms an uninterruptable power supply (UPS) to ensure continued operation in the event of an AC powerline brownout or failure. During AC faults the battery supplies power to the backplane.

Power Functions

The whole PLC power network is quite complicated with a variety of protection, isolation, and post-regulation functions. This power function can also be duplicated in a system to allow hot backup and hot-swapping in case of a power fault. In some cases isolated power supplies are implemented on a modular card.

PLC functions take power from the power rail and are organized into separate functional modules that have hot-swap controllers to prevent inrush current surges during hot installation/removal. The modules' power inputs can usually withstand a higher voltage than the power rail, because high-voltage spikes can occur at those inputs. Each functional module has its own local converters to generate regulated +5V, +3.3V, and other local power rails. In cases where a regulated DC-DC supply is not required, Maxim's transformer drivers can be used to enable a designer to quickly and simply design a highly efficient isolated DC-DC converter. The CPU or FPGA typically requires even lower voltages for the high-performance core. Analog I/Os can require ±15V or higher voltages for op amps and/or analog-output conditioners. A PLC can also provide a regulated power output of +24V for smart sensors, other remote equipment, and analog 4–20mA current-loop interfaces.



Block diagram of a typical PLC power chain.

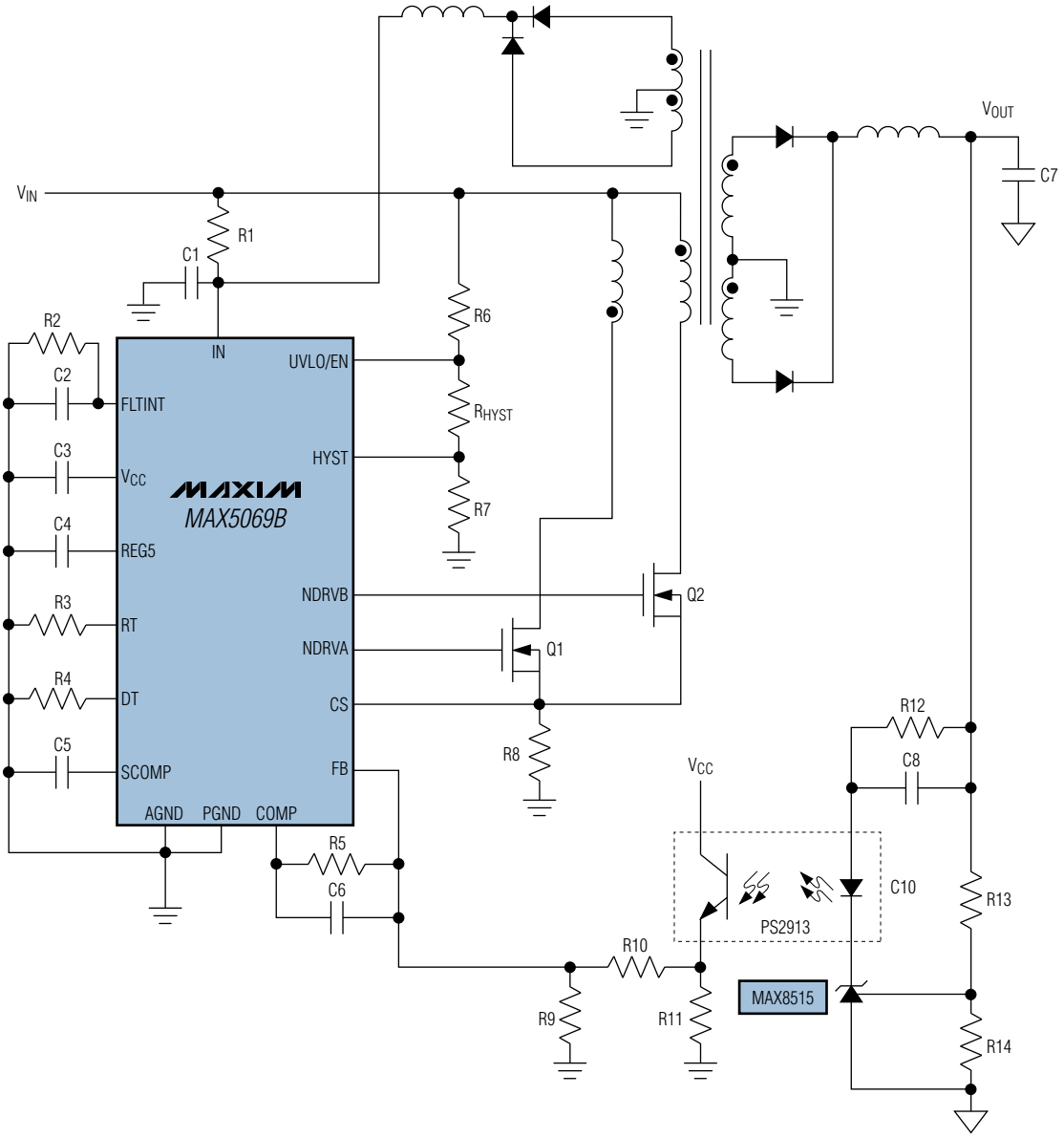
Flexible Solution for Push-Pull and Half-/Full-Bridge Power Supplies, Ideal for High-Power Applications

MAX5069

The MAX5069 is a high-frequency, current-mode PWM controller with dual MOSFET drivers. The IC integrates everything necessary for implementing AC-DC or DC-DC fixed-frequency power supplies. Isolated or nonisolated, push-pull and half-/full-bridge power supplies are easily constructed using either primary- or secondary-side regulation. An input undervoltage lockout (UVLO) programs the input-supply startup voltage and ensures proper operation during brownout conditions. The MAX5069 operates at over 100W.

Benefits

- Wide load range provides design flexibility
  - Can provide over 100W output power
- Eases design by accepting wide input voltage range
  - Rectified 85V AC to 265V AC input range
  - 36V DC to 72V DC input range
  - UVLO assures proper startup and brownout response



Secondary-side, regulated, isolated power supply. The dashed line encompasses both functions of the optoisolator.

High Level of Integration Reduces Design Cost and Complexity in Universal Offline Power Supplies

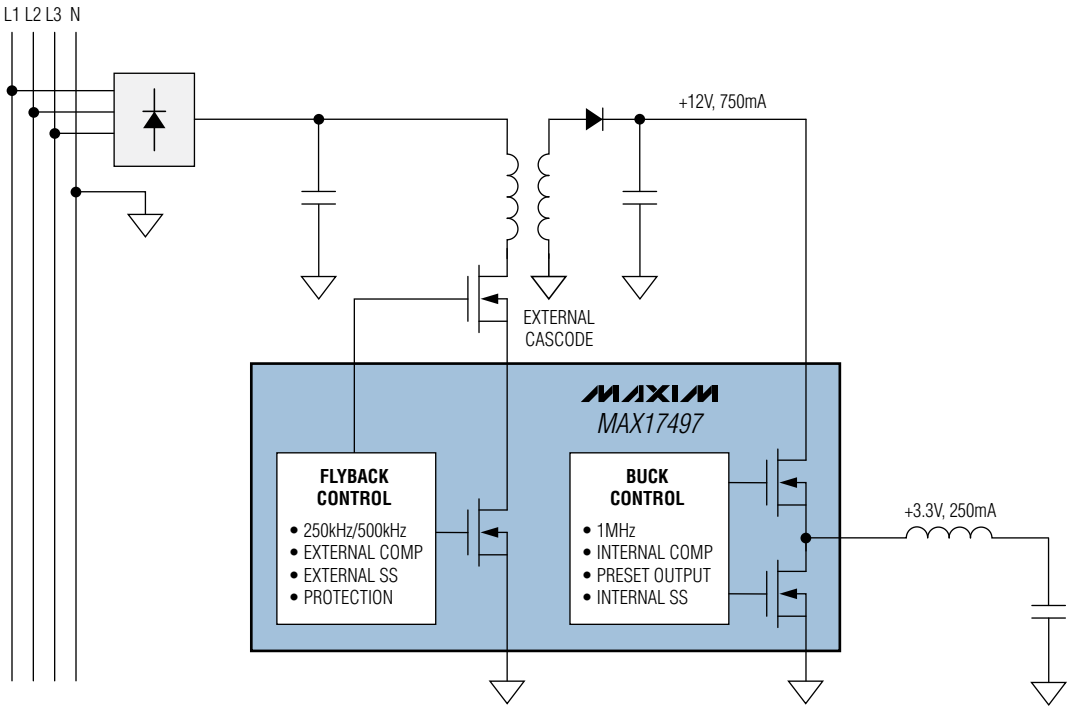
MAX17497, MAX17498

The MAX17497 simplifies your power design by eliminating multiple discrete components. This multiple-output device integrates the control circuitry needed for a universal (85V to 265V AC) flyback/forward power supply. It also integrates a secondary-side synchronous buck regulator with on-board MOSFETs.

The MAX17497 combines a current mode PWM flyback/forward regulator, which contains all the control circuitry required for design of wide input voltage nonisolated power supplies, and a synchronous buck regulator. The MAX17498 is an easy to use current mode PWM flyback/forward regulator for offline AC-DC or stand-alone DC-DC flyback/forward/boost applications.

Benefits

- High integration reduces BOM
  - Two on-board regulators: AC-DC and DC-DC combined
  - Power FETs integrated
- Enables small solution
  - Fast 500kHz switching allows use of small external components



Simplified application circuit for the MAX17497.

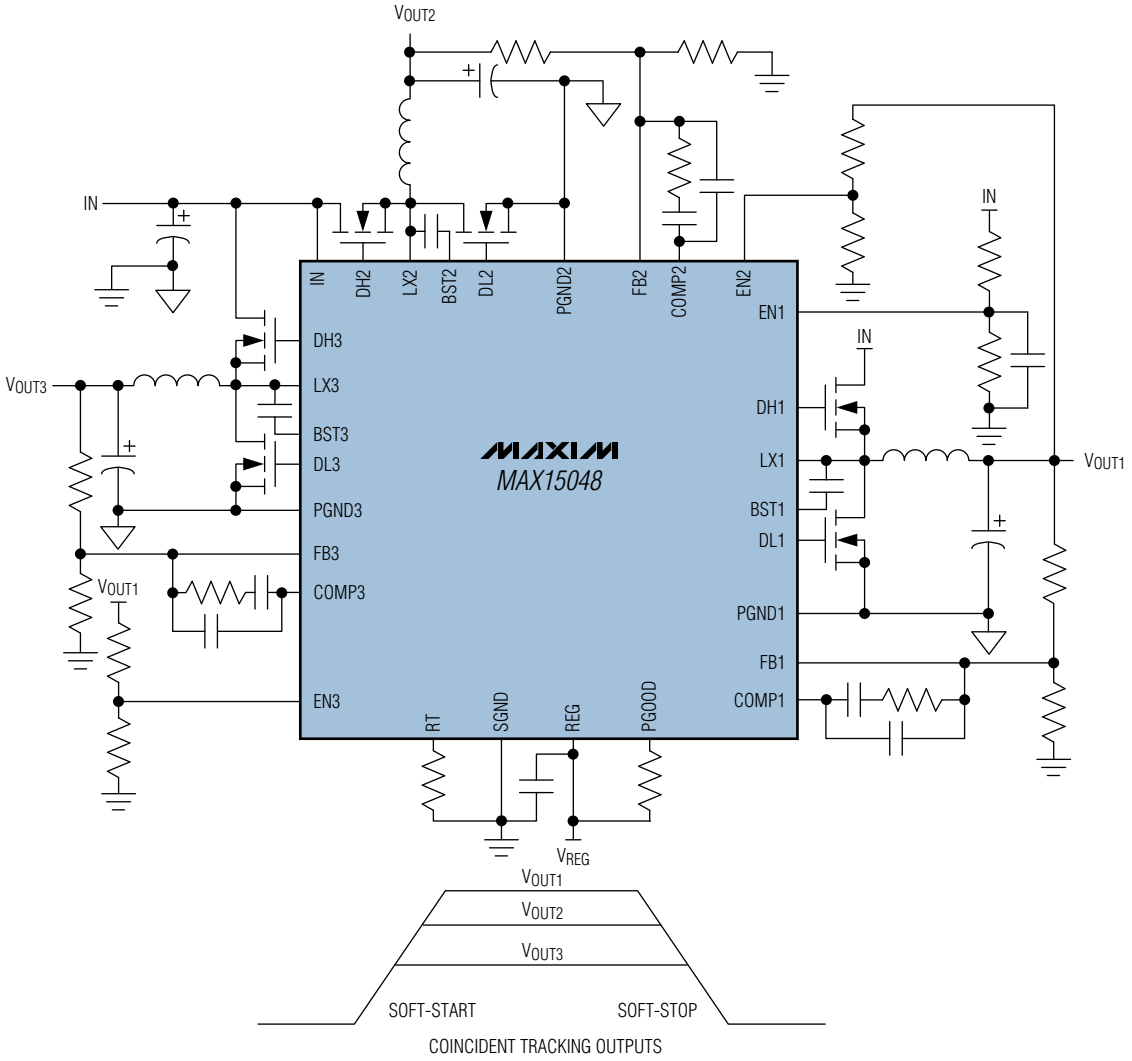
Save Space and Costs by Integrating Three Switching Controllers

MAX15048/MAX15049

The MAX15048/MAX15049 are triple-output, PWM, step-down DC-DC controllers with tracking (MAX15048) and sequencing (MAX15049) options. The devices operate over the 4.7V to 23V input voltage range. Each PWM controller provides an adjustable output down to 0.6V and delivers up to 15A of load current with excellent load and line regulation. The options of coincident or ratiometric tracking (MAX15048) or output sequencing (MAX15049) allow tailoring of the power-up/power-down sequence, depending on the system requirements.

Benefits

- Simplify design of power supplies for CPUs that require rail tracking and sequencing
  - Built-in tracking and sequencing provides solution for complex rail relationships on advanced CPUs and FPGAs
  - Triple controller provides three rails in one IC
- External power MOSFETs allow precise solution sizing to meet needs



Typical operating circuit of the MAX15048.

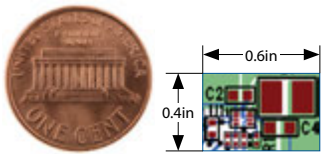
Save Cost and Reduce Solution Footprint with Integrated DC-DC Converters That Power Off a 24V Nominal Industrial Bus

MAX15062, MAX17501*, MAX17502**

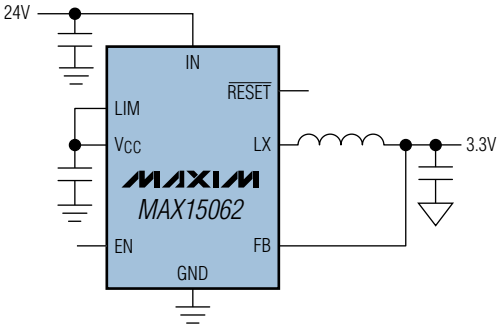
The MAX15062, MAX17501, and MAX17502 make a family of high-voltage, internal FET synchronous buck regulators built for space-constrained automation and control applications. Designed specifically for industrial applications, these devices operate off the 24V nominal rail while supporting supply line transients up to 65V. This family of high-voltage regulators integrate switching MOSFETs while using synchronous rectification to significantly increase power-conversion efficiency and reduce the overall solution footprint. The MAX15062 can support a 4V to 36V input voltage range, while delivering 300mA output current. The MAX17501 and MAX17502 can support a 3.5V to 65V input voltage range while delivering up to 500mA and 1A output current, respectively.

Benefits

- High conversion efficiency reduces heat build-up
  - Synchronous switches eliminate low-side freewheeling diode losses
- Saves space
  - Small 2mm x 2mm (MAX15062) and 3mm x 3mm (MAX17501/2) packages
  - On-board power FETs reduce external components
  - High 700kHz switching frequency reduces external component size



Total solution board area of the MAX15062.



Typical operating circuit for the MAX15062.

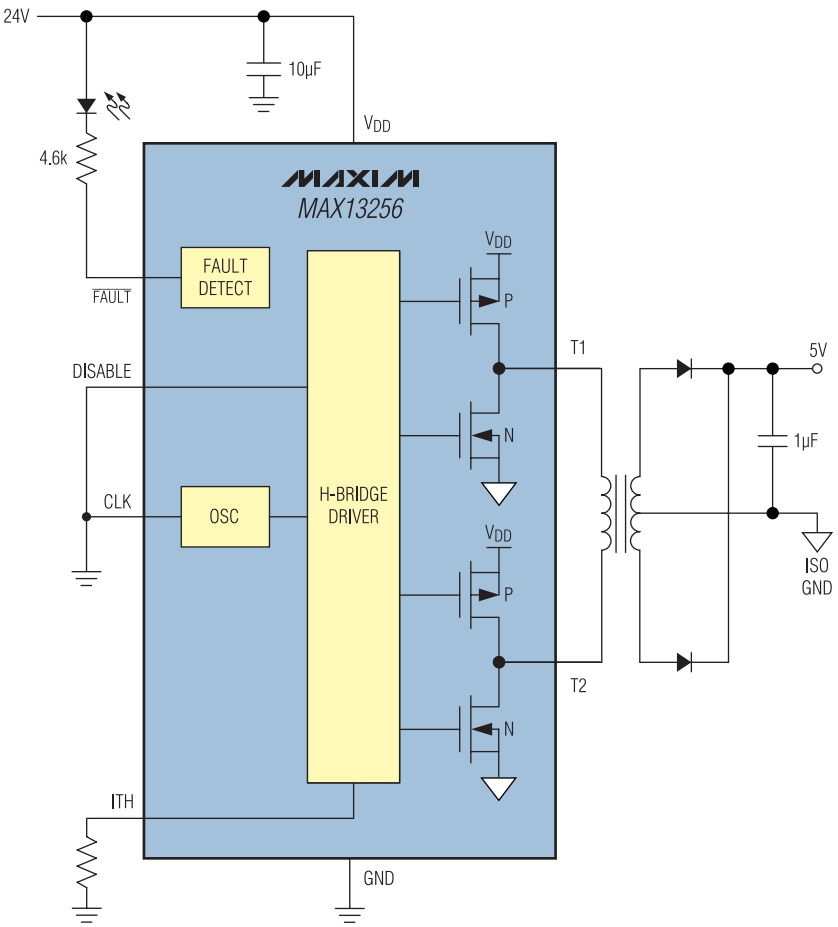
*Future product—contact the factory for availability.

36V Transformer Driver Simplifies Isolated Power

MAX13256

The MAX13256 enables a simple and flexible approach to the design of an isolated DC-DC supply. The MAX13256 operates from a wide 8V to 36V DC supply and can deliver up to 10W of isolated power. Maxim's transformer drivers provide system designers with greater flexibility by using an external transformer's winding ratio to allow the selection of virtually any isolated output voltage.

The MAX13256 H-bridge transformer driver offers higher integration with short-circuit protection and overtemperature protection to help prevent system level failures. Packaged in a space-saving (3mm x 3mm) TDFN, this integrated device reduces design complexity and lowers BOM cost, giving system designers the simplest solution for isolated power-supply circuits in industrial, smart metering, and medical applications.



Typical application circuit for the MAX13256.

Benefits

- Simplifies isolated power generation
  - 8V to 36V supply allows widest input range, adaptable for many different voltage systems
  - Delivers up to 10W of isolated power
  - Provides up to 90% efficiency
- Saves space
  - Eliminates up to 16 discrete components
  - Tiny (3mm x 3mm) 10-pin TDFN package
- Prevents system-level failures
  - Fault indicator
  - Short-circuit protected
  - Overtemperature protected
  - Robust temperature range (-40°C to +125°C)

Recommended Solutions

Analog Input Functions

Part	Description	Features	Benefits
Active Filters			
MAX7409/10 MAX7413/14	5th-order, switched-capacitor, lowpass filters (Bessel or Butterworth)	Clock or capacitor-adjustable corner frequency to 15kHz, 1.2mA supply current	Save space over discrete implementations.
MAX7422–MAX7425	5th-order, switched-capacitor, lowpass filters (elliptic, Butterworth, or Bessel)	Clock or capacitor-adjustable corner frequency to 45kHz, 3mA supply current, 8-pin µMAX package	Save space over discrete implementations.
MAX274/75	4th-order/8th-order, 150kHz/300kHz lowpass/bandpass filters	Resistor programmable, continuous-time filters, -89dB THD, low noise	Ease anti-aliasing filtering.
ADCs			
MAX11040K	24-bit, 4-channel, simultaneous-sampling sigma-delta ADC	64ksps, internal reference, 38-pin TSSOP package	Reduces firmware complexity, capturing accurate phase and magnitude information on up to 32 channels.
MAX11200–MAX11203, MAX11205–MAX11213	24-/20-/18-/16-bit, ultra-low-power, single-channel, delta-sigma ADCs with internal buffers	3V supply, 0.69mW, industry-leading effective resolution per unit power, tiny µMAX/QSOP package, four built-in GPIOs	Integrated GPIOs save cost by eliminating isolators between multiplexer and microcontroller.
MAX11160*/1*, MAX11162/3, MAX11164*/5*, MAX11166*/7*	16-bit, 1-channel, 500ksps/250ksps SAR ADCs with internal reference	5ppm/°C internal reference, 0 to 5V or ±5V input ranges, 1 LSB INL and DNL, 94dB SNR	Internal reference and bipolar inputs make for pin-compatible upgrade in industry-standard 10-pin µMAX and TDFN packages.
MAX1300*/01/02*/03	16-bit, 8-/4-channel SAR ADCs with software-programmable input ranges	115ksps; up to ±12V bipolar input range or down to 0 to 2.048V unipolar range, ±16.5V overvoltage protection (OVP)	Software-programmable input ranges save design time and eliminate external circuitry.
MAX1402/03	18-bit, 5-channel, sigma-delta ADCs	4.8ksps, 0.75mW, 28-pin SSOP package, matched current sources for RTDs	Precision current output sources eliminate signal-conditioning circuitry.
Hot-Swap Controllers			
MAX5924/25/26	1V to 13.2V hot-swap controllers require no R_{SENSE}	Sense resistor not needed, hot-swaps 1V to 13.2V range of supplies	Save cost and board space; single device accommodates wide range of supply rails.
MAX5932	Positive high-voltage, hot-swap controller	Hot swaps wide 9V to 80V supplies; overcurrent, overvoltage, and undervoltage protection	One device accommodates wide range of backplane supply voltages.
MAX5943	7.5V to 37V hot-swap controller with diode ORing	Integrates low-voltage-drop ORing and hot-swap function, programmable current-limit/ circuit-breaker function, UL-recognized protective circuit	Integrated hot-swap and diode ORing function saves space.

(Continued on following page)

*Future product—contact the factory for availability.

Part	Description	Features	Benefits
Multiplexers			
MAX14778	Above/below the rails dual 4-to-1 multiplexers	High ±25V signal range, low-voltage 3V to 5.5V supply, 1.5Ω (max) R_{ON}, ±6kV ESD	Simplifies system designs by reducing high-voltage power-supply dependency.
MAX354/55	Fault-protected analog multiplexers	Fault protection up to ±40V, 0.02nA (typ) leakage currents, digital inputs are CMOS/TTL compatible	High fault protection eliminates external protection circuitry.
MAX14752/53	High-voltage 8:1 and dual 4:1 analog multiplexers	Wide ±10V to ±36V (max) power-supply range, 60Ω (typ) on-resistance, low 0.03Ω (typ) R_{ON} flatness over common-mode voltage	High supply voltage eliminates external protection circuitry.
Operational Amplifiers			
MAX9943/44	38V precision, single and dual op amps	Wide 6V to 38V supply range, low 100µV (max) input offset voltage, drives 1nF loads	Wide operating voltage range and precision performance under most capacitive loads.
MAX9945	38V CMOS input precision op amp	Wide 4.75V to 38V supply range, low input-bias current, rail-to-rail output swing	High voltage and low femto-amp input-bias current easily allow high-voltage interfacing with ultra-high ohmic sensors.
MAX9632/9633	Precision 30V ultra-low-noise op amps with ±8kV ESD rating	0.94nV/√Hz, 125µV (max) offset, offset temp coefficient of 0.5µV/°C, 55MHz gain bandwidth (GBW)	High-accuracy signal conditioning across wide frequencies and at high gain able to drive 24-bit sigma-delta ADCs.
MAX44251/52*	Ultra-precise auto-zero op amps	20V low-noise, low-offset op amps in SOT23	Ensure calibrated signal conditioning over temperature and time.
Precision Resistors			
MAX5490/91/92	Precision-matched thin-film resistor-dividers	Ratiometric 1ppm/°C (typ) temperature drift, 80V working voltage	Maintain system accuracy over temperature variations; work well in high-voltage applications.
MAX5427/28/29	Low-cost, one-time-programmable (OTP) digital potentiometers with up/down interface	1µA (max) standby current (no programming), 35ppm/°C end-to-end and 5ppm/°C ratiometric tempco	Increase power savings and better measurement stability over temperature changes.
MAX5494–MAX5499	10-bit, dual, nonvolatile voltage-divider or variable resistor with SPI interface	1µA (max) standby current (no programming), 35ppm/°C end-to-end and 5ppm/°C ratiometric tempco	Improve power saving and increase performance over temperature variations.

(Continued on following page)

*Future product—contact the factory for availability.

Part	Description	Features	Benefits
Signal Conditioners			
MAX1452	Low-cost, precision sensor signal conditioner	Multitemperature calibration, current and voltage excitation, fast 150µs response, single-pin programmable, 4–20mA applications	High accuracy simplifies designs in multiple platforms; reduces inventory and cost
MAX1454	Precision sensor signal conditioner with over/reverse voltage protection	45V over/reverse voltage protection, input fault detection, 16-bit resolution with 6V/V to 2048V/V signal-path gain	Offers robustness and protects against power transient/surge; adds safety and offers low-cost solution.
MAX1464	Low-power, low-noise, multichannel, digital sensor conditioner	Integrated 16-bit ADC, DACs, and CPU; programmable compensation algorithm; digital, analog, and PWM outputs; 4–20mA application	Directly interfaces with microprocessors/controllers; provides amplification, calibration, linearization, and temperature compensation for a variety of sensors.
Thermal Management			
DS600	Precision, analog-output temperature sensor	Industry's highest accuracy: ±0.5°C from -20°C to +100°C	Best cold-junction compensation accuracy for superior thermocouple measurement.
DS7505	Low-voltage, precision digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation, industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply voltage reduction from LM75.
MAX6631	Low-power, digital temperature sensor	±1°C accuracy from 0°C to +70°C, 50µA (max) supply current	Low supply current extends battery life.
MAX31855	Thermocouple-to-digital converter	Built-in cold-junction compensation; versions available for Type E, J, K, N, R, S, and T thermocouples	Simplest thermocouple interface, no external components needed.
Voltage Supervisors			
MAX16023/24	Battery-backup switchover ICs with integrated regulated output	Low power, small TDFN package, integrated regulated output	Retain system configuration data during brownout.
MAX6381	Single-voltage supervisor	Multiple threshold and timeout options	Versatile for easy design reuse; saves space in small modules.
MAX6495	72V overvoltage protector	Protects against transients up to 72V; small, 6-pin TDFN-EP package	Increases system reliability by preventing component damage due to high-voltage transients; saves space; easy to use.
MAX6720	Triple-voltage supervisor	Two fixed thresholds and one adjustable threshold	Integration shrinks design size.
MAX6746	Capacitor-adjustable watchdog timer and reset IC	Capacitor-adjustable timing, 3µA supply current	Versatile for easy design reuse; saves space in small modules.
MAX6816/17/18	Single, dual, and octal switch debouncers	±15kV ESD protection	High reliability; easy to use.

Analog Output Functions

Part	Description	Features	Benefits
HART			
DS8500	HART modem	HART compliant, integrated digital filter, 5mm x 5mm x 0.8mm TQFN package, 3.6864MHz clock, 285µA active-mode current	Single-chip solution with small PCB footprint saves space and power.
Operational Amplifiers			
MAX9943/44	38V high-output-drive, single and dual op amps	Output voltage swing to 38V, output-current drive exceeds 50mA, drives 1nF load	Easily drive 4–20mA loops at 24V.
MAX4230–MAX4234	High-output-drive, 10MHz, 10V/µs rail-to-rail input/output (RRIO) single, dual, and quad op amps	200mA peak current output, RRIO, consumes only 1mA and drives 780pF	RF immunity, output current, and slew rate ideal for driver applications, active filters, or buffers.
MAX4475–MAX4478	Low noise, low distortion, 10MHz single, dual, and quad op amps	Low THD+N (0.0002%), low 4.5nV/√Hz noise, low offset, up to 42MHz GBW	Ideal to drive ADCs without adding additional noise while maintaining the effective number of system bits (ENOB).
MAX9650/51	High-current, high-voltage RRIO single and dual op amps	20V operating voltage, 1.3A peak-current drive, 40V/µs slew rate	Handle system outputs in rugged industrial environments.
Precision DACs			
MAX5134–MAX5139	1-/2-/4-channel, 16-/12-bit DACs with pin-programmable zero or midscale power-up	Output set to zero or midscale upon power-up	Add additional safety during power-up.
MAX5661	Single-channel DAC with 16-bit voltage- or current-buffered output	16-bit, voltage- or current-buffered output, integrated high-voltage current and voltage amplifiers, serial interface	Reduces external component count; reduces cost.
MAX5214/16	Ultra-low-power, 1-channel 14-/16-bit DAC	14-/16-bit voltage-output DAC, quiescent current < 80µA max, SPI interface	Ideal for loop-powered applications without sacrificing precision and accuracy.
MAX5500	4-channel, 12-bit DAC with precision amplifier-output conditioners	Output conditioners, 0.85mA of quiescent current (I_Q)	Needs no external amplifiers; makes equipment more compact.
Signal Conditioners			
MAX1452	Low-cost, precision sensor signal conditioner	Multitemperature calibration, current and voltage excitation, fast 150µs response, single-pin programmable, 4–20mA applications	Integrated signal-conditioner simplifies designs and lowers development time; fits a wide range of sensor applications.
MAX1454	Precision sensor signal conditioner with over/reverse voltage protection	45V over/reverse voltage protection, input fault detection, 16-bit resolution with 6V/V to 2048V/V signal-path gain	Offers robustness and protects against power transient/surge; adds safety and offers low-cost solution.
MAX1464	Low-power, low-noise, multichannel, digital sensor conditioner	Integrated 16-bit ADC, DACs, and CPU; programmable compensation algorithm; digital, analog, and PWM outputs; 4–20mA application	Directly interfaces with microprocessors/controllers; provides amplification, calibration, linearization, and temperature compensation for a variety of sensors.
MAX15500	Industrial analog current/voltage output conditioner	Outputs protected against overcurrent, short to ground or supply up to ±35V	Enhances robustness for higher reliability outputs.

(Continued on following page)

Part	Description	Features	Benefits
Thermal Management			
MAX6631	Low-power digital temperature sensor	±1°C accuracy from 0°C to +70°C, 50µA (max) supply current	Very low-supply current for minimal impact on system power usage.
DS7505	Low-voltage, precision digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation; industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply voltage reduction from LM75.
DS18B20	Precision 1-Wire digital temperature sensor	±0.5°C accuracy; 1-Wire interface; 64-bit, factory-lasered ID code	Connects multiple precision temperature sensors with less wire than any competitive solution.
Voltage Supervisors			
MAX16023/24	Battery-backup switchover ICs with integrated regulated output	Low power, small TDFN package, integrated regulated output	Retain system configuration data during brownout.
MAX6381	Single-voltage supervisor	Multiple threshold and timeout options	Versatile for easy design reuse; saves space in small modules.
MAX6495	72V overvoltage protector	Protects against transients up to 72V; small, 6-pin TDFN-EP package	Increases system reliability by preventing component damage due to high-voltage transients; saves space; easy to use.
MAX6720	Triple-voltage supervisor	Two-fixed thresholds and one adjustable threshold	Integration shrinks design size.
MAX6746	Capacitor-adjustable watchdog timer and reset IC	Capacitor-adjustable timing, 3µA supply current	Versatile for easy design reuse; saves space in small modules.

Digital I/O Functions

Part	Description	Features	Benefits
Digital I/O Modules			
MAX14830	Quad SPI/I^2C UART with 128-byte FIFOs	24Mbps (max) data rate, automatic transceiver control, 16 GPIOs, 7mm x 7mm 48-pin TQFN package	Serial interface reduces cost for isolators.
MAX14824	IO-Link master transceiver	IO-Link master transceiver; a Type 1, Type 2, and Type 3 digital input; addressable SPI interface	Addressable SPI reduces cost for isolation in high-port-count masters.
Thermal Management			
DS7505	Low-voltage, precision digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation; industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply voltage reduction from LM75.
DS18B20	Precision 1-Wire digital temperature sensor	±0.5°C accuracy; 1-Wire interface; 64-bit, factory-lasered ID code	Connects multiple precision temperature sensors with less wire than any competitive solution.
MAX6631	Low-power, digital temperature sensor	±1°C accuracy from 0°C to +70°C, 50µA (max) supply current	Very low-supply current for minimal impact on system power usage.
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MAX6495	72V overvoltage protector	Protects against transients up to 72V; small, 6-pin TDFN-EP package	Increases system reliability by preventing component damage due to high-voltage transients; saves space; easy to use.
MAX6720	Triple-voltage supervisor	Two-fixed, and one adjustable thresholds	Integrates three voltage monitors into one to shrink design size.
MAX6746	Capacitor-adjustable watchdog timer and reset IC	Capacitor-adjustable timing, 3µA supply current	Versatile for easy design reuse; saves space in small modules.

Fieldbus Functions

Part	Description	Features	Benefits
Interface Transceivers			
MAX14770E	PROFIBUS transceiver	±35kV (HBM) ESD tolerance, -40°C to +125°C automotive temperature range, small (3mm x 3mm) TQFN package	Industry's highest ESD protection makes PLC more robust.
MAX13450E/51E	RS-485 transceiver with pin-selectable termination resistors	Integrated 100Ω and 120Ω termination resistors, FAULT indication, flexible logic interface	Allow remote configuration of the line termination, which simplifies system installation.
MAX3535E	Isolated RS-485 transceiver	3V to 5V operation, $2500V_{RMS}$ isolated RS-485/RS-422 transceivers, ±15kV ESD protection	Eliminates the need for external isolation components.
MAX13442E/43E/44E	Fault-protected RS-485 transceivers	±80V fault-protected half-duplex operation, 5V transceiver (250kHz/10MHz)	Simplify design by eliminating external components such as TVSs and PTCs.
MAX13430E	RS-485 transceiver with V_L pin in tiny µDFN	3V to 5V operation, integrated V_L pin (down to 1.6V), 10-pin µMAX/µDFN	Tiny package with integrated V_L pin saves board space and communicates with low-voltage FPGAs and microcontrollers.

CPU Functions

Part	Description	Features	Benefits
Microcontrollers			
MAXQ2010	Low-power, 16-bit mixed-signal LCD microcontroller	64KB flash; 8-channel, 12-bit SAR ADC; 160-segment LCD, hardware multiplier; SPI/I²C and two USART interface; 370nA stop-mode current	High integration in a single chip; low power consumption.
MAXQ8913	16-bit mixed-signal microcontroller	64KB flash; 7-channel, 12-bit SAR ADC; dual, 10-bit differential DACs; dual, 8-bit single-ended DACs; four op amps; a temp sensor; two current sinks; USART/SPI/I²C interface	High integration provides a true mixed-signal one-chip solution.
UARTs			
MAX3107	SPI/I²C UART	24Mbps (max) data rate, 128-byte FIFOs, automatic RS-485 transceiver control, 4 GPIOs, 24-pin SSOP or small 3.5mm x 3.5mm TQFN	Eases system design.
MAX3109	Dual serial UART with 128-word FIFOs	24Mbps (max) data rate, 128-byte FIFOs, automatic RS-485 transceiver control, 8 GPIOs, 32-pin TQFN	Eases system design.
Thermal Management			
DS7505	Low-voltage, precision digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation, industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply voltage reduction from LM75.
DS18B20	Precision 1-Wire digital temperature sensor	±0.5°C accuracy, 1-Wire interface, 64-bit, factory-lasered ID code	Connects multiple precision temperature sensors with less wire than any competitive solution.
MAX6602	5-channel precision temperature monitor	One local and four remote digital sensing channels, ±1°C accuracy	Reduces board space compared to five separate temperature sensors.
Voltage Supervisors			
MAX16023/24	Battery-backup switchover ICs with integrated regulated output	Low power, small TDFN package, integrated regulated output	Retain system configuration data during brownout.
MAX6381	Single-voltage supervisor	Multiple threshold and timeout options	Versatile for easy design reuse; saves space in small modules.
MAX6495	72V overvoltage protector	Protection against transients up to 72V; small, 6-pin TDFN-EP package	Increases system reliability by preventing component damage due to high-voltage transients; saves space; easy to use.
MAX6720	Triple-voltage supervisor	Two fixed thresholds and one adjustable threshold	Integrates three voltage monitors to shrink design size.
MAX6746	Capacitor-adjustable watchdog timer and reset IC	Capacitor-adjustable timing, 3µA supply current	Versatile for easy design reuse; saves space in small modules.

Nonisolated and Isolated Power-Supply Functions

Part	Description	Features	Benefits
Offline AC-DC, DC-DC Controllers			
MAX17499/500	Isolated/nonisolated current-mode PWM controllers ideal for flyback/ forward topologies	85V AC to 265V AC universal offline input voltage range (MAX17500), 9.5V DC to 24V DC input voltage range (MAX17499), programmable switching frequency up to 625kHz, 1.5% reference accuracy	Topology allows wide power range for use in multiple offline applications.
MAX5069	Isolated/nonisolated current-mode PWM controller with dual FET drivers ideal for push-pull and half-/full-bridge power supplies	85V AC to 265V AC universal offline input voltage range (MAX5069A/B), 10.8V DC to 24V DC input voltage range (MAX5069C/D), programmable switching frequency up to 2.5MHz, programmable UVLO and UVLO hysteresis	Programmable switching frequency enables optimization of magnetic and filter components, reducing solution size.
MAX17497/98	Current-mode regulator for universal AC-DC flyback/ forward topologies with built-in synchronous buck regulator	1x nonisolated flyback/ forward regulator + 1x internal secondary-side step-down regulator; 250kHz/500kHz flyback regulator frequency and 1MHz secondary buck regulator frequency; programmable slope compensation for flyback regulator and internal compensation for secondary buck regulator	Two supplies in single-chip solution provide ease of design and high accuracy, and reduce solution cost and size.
Nonisolated DC-DC Controller			
MAX15046A/B	40V, high-performance synchronous buck controller	4.5V to 40V input voltage range, 0.6V to (0.85)V_{IN} output voltage range, 100kHz to 1MHz programmable switching frequency, ±1% accurate voltage reference	Support the 24V industrial supply voltage with ample margin; programmable switching frequency allows optimizing for smallest solution size and efficiency.
MAX15023/26	Wide V_{IN}, dual-/single-output synchronous buck controllers	4.5V to 28V input voltage range, 0.6V to (0.85)V_{IN} output voltage range, 200kHz to 1MHz programmable switching frequency, ±1% accurate voltage reference, independent EN and PGOOD for each PWM channel (MAX15023)	Programmable switching frequency allows optimizing for smallest solution size and efficiency.
MAX15048/49	Triple-output synchronous buck controllers with tracking/ sequencing	4.7V to 23V input voltage range, 200kHz to 1.2MHz programmable switching frequency, 120 degrees out-of-phase operation, digital soft-start and soft-stop	Out-of-phase operation reduces input filter requirements, saving cost and size; soft-start and soft-stop enable glitch free power-up and power-down.

(Continued on following page)

Part	Description	Features	Benefits
Nonisolated DC-DC Internal FET Regulators			
MAX15062*	36V, synchronous, micro buck regulator	4V to 36V input voltage range, fixed 700kHz switching frequency, integrated high-side and low-side FETs, internal compensation	Internal MOSFETs and compensation increase efficiency, while reducing solution size and cost.
MAX17501*/02*	65V, high-efficiency current-mode synchronous buck regulators	3.5V to 65V input voltage range, 500mA (MAX17501) and 1A (MAX17502) output current capability, auto PFM/PWM operation, ±1% feedback voltage accuracy	Support 48V industrial supply voltage with ample margin.
MAX5033/35	76V, high-efficiency, MAXPower buck regulators	7.5V to 76V input voltage range, 500mA (MAX5033) and 1A (MAX5035) output current capability, internal compensation, 270µA I_Q at no load	Support the 48V industrial supply voltage with ample margin; internal compensation reduces solution cost.
MOSFET/Rectifier Drivers			
MAX15024/25	Single/dual high sink/source current gate drivers	8A/4A peak sink/source current (MAX15024), 4A/2A peak sink/source current (MAX15025), 4.5V to 28V input voltage range, CMOS and TTL logic-level inputs	Simplify design with a very low propagation delay and a thermally enhanced package.
MAX15070	High-speed single low-side MOSFET driver	4V to 14V single power-supply rail, 7A/3A peak sink/source current, 12ns propagation delay	Simplifies design with a very low propagation delay and a thermally enhanced package; increases efficiency with low rise/fall time.
MAX15012/13	175V high-speed, half-bridge MOSFET drivers	Up to 175V input operation, 2A peak sink/source current, 35ns propagation delay	Enable high-voltage, high-power, and high-frequency designs with very low and matched propagation delays between drivers.
Transformer Drivers			
MAX13256	36V H-bridge transformer driver for isolated supplies	Wide 8V to 36V supply, up to 10W of isolated power, up to 90% efficiency, short-circuit protection	Simple open-loop circuit speeds isolated power-supply design.
MAX253	Transformer driver for isolated power with RS-485/PROFIBUS interfaces	Single 5V or 3.3V supply, low 0.4µA current shutdown mode, pin-selectable frequency of 350kHz or 200kHz, µMAX package	Simple open-loop circuit speeds power-supply design.
MAX256	Low-voltage transformer driver for isolated power	3W output power, full bridge, integrated protection	Simple open-loop circuit speeds power-supply design.
MAX845	Low-voltage transformer driver for isolated power	750mW output power, half bridge	Simple open-loop circuit speeds power-supply design.

(Continued on following page)

*Future product—contact the factory for availability.

Part	Description	Features	Benefits
Thermal Management			
DS7505	Low-voltage, precision digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation, industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply voltage reduction from LM75.
MAX6602	5-channel precision temperature monitor	Local and four remote digital sensing channels, ±1°C accuracy	Reduces board space compared to five separate temperature sensors.
MAX6509	Resistor-programmable temperature switches	Resistor-programmable trip temperature, 6-pin SOT23 package	Simple protection against damage from overtemperature events.
MAX6639	2-channel temperature monitor and PWM fan controller	Internal and external temperature measurement, closed-loop RPM control	Closed-loop control over fan speed minimizes noise and power.
Voltage Supervisors			
MAX16023/24	Battery-backup switchover ICs with integrated regulated output	Low power, small TDFN package, integrated regulated output	Retain system configuration data during brownout.
MAX6381	Single-voltage supervisor	Multiple threshold and timeout options	Versatile for easy design reuse; saves space in small modules.
MAX6495	72V overvoltage protector	Protection against transients up to 72V, small, 6-pin TDFN-EP package	Increases system reliability by preventing component damage due to high-voltage transients; saves space; easy to use.
MAX6720	Triple-voltage supervisor	Two fixed thresholds and one adjustable threshold	Integrates three voltage monitors to shrink design size.
MAX6746	Capacitor-adjustable watchdog timer and reset IC	Capacitor-adjustable timing, 3µA supply current	Versatile for easy design reuse; saves space in small modules.

Sensors

Overview

Introduction

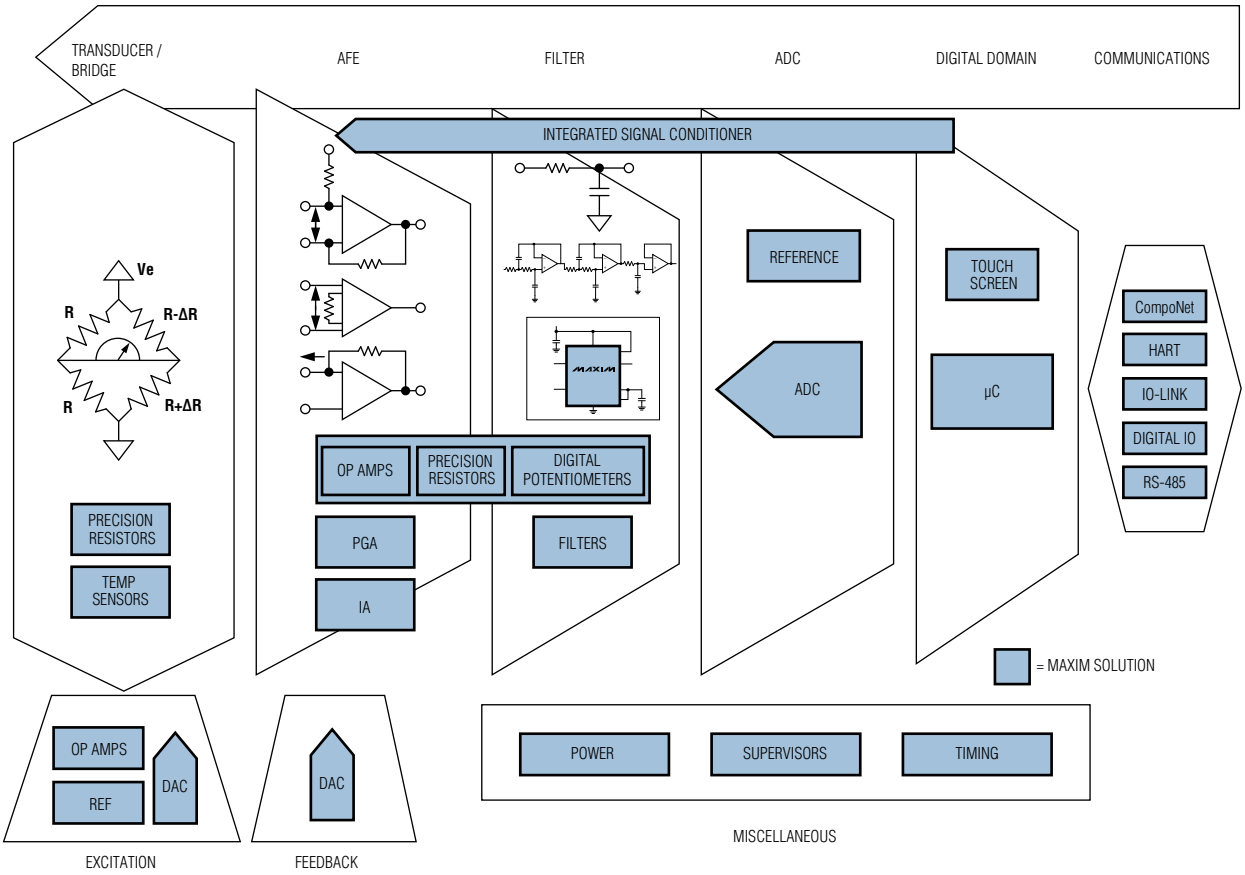
Maxim offers a range of products extending from sensors for properties such as temperature, light, acceleration, etc., to products that shape and convert a sensor's electrical signals into usable information.

A sensor is a device that measures a physical property and is generally used to monitor and control an event or process. Examples include sensors for measuring the temperature of a room or of a blast furnace; the pressure in a tire or in a steam turbine; the weight of an item purchased at the grocery store or of a vat of molten steel. The use of sensors permeates our personal lives and our factories. We depend inextricably on the operation and accuracy of sensors to ensure we are receiving the goods and services that we paid for to live more productive and comfortable lives and to run our industrial processes safely and efficiently.

A complete sensor assembly includes a transducer (to transform one physical quantity to another: weight, pressure, temperature, humidity, acceleration, or light to an electrical signal), a housing, signal conditioning and communications circuitry, and a connector. Some transducers are resistive elements that require external excitation to create a measurable voltage. Other transducers generate their own voltages or currents in response to physical properties.

The signals coming from transducers are usually very small and require optimized interface circuits to provide adequate gains without introducing noise that reduces accuracy. Sensor assemblies are often located far from their processing point, so along with signal amplification, the sensor knowledge domain also includes signal communications to ensure the delivery of accurate signals to a processing point.

The sensor "signal chain" requires processing for sensor excitation, sensor amplification, signal filtering and conditioning, and the transformation of signals from the analog-to-digital domain, and sometimes back again. Outside the signal chain there are other stringent requirements for power provisioning and management, as well as signal communication among devices/systems and secure data transmission.



Block diagram of a basic sensor system for industrial processes. For a list of Maxim's recommended sensor solutions, please go to: www.maxim-ic.com/sensor.

Pressure Sensors and Weigh Scales (Force Sensing)

Overview

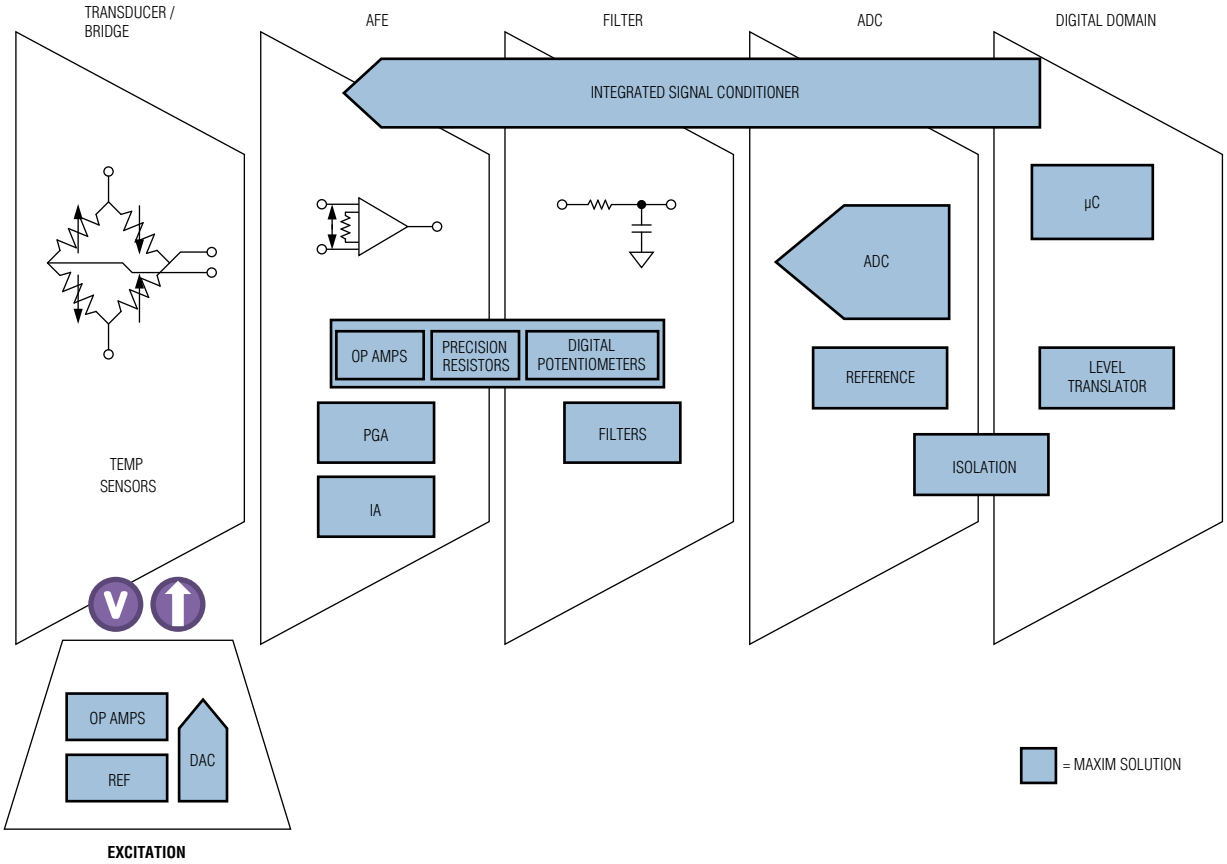
The need to detect and measure pressure and weight is a very common requirement for modern industrial control and system monitoring. Pressure measurement is especially important, as it is also used indirectly to measure flow, altitude, and other properties. Pressure-and weight-measurement devices can be regarded as "force sensors," since force is the property that affects the transducers' outputs. The applications for force sensors are vast and range from vacuum gauges to heavy machinery weigh scales, industrial hydraulic equipment, and manifold absolute pressure (MAP) sensors for internal-combustion engines. Each application has its own diverse needs for precision, accuracy, robustness, and cost.

Although there are several methods and technologies for measuring force, the most commonly used measurement element is the strain

gauge. The two most common types of strain gauges are the metal-foil type used in a variety of weight/pressure sensors, and the semiconductor-based piezoresistive transducers, widely used to measure pressure. Compared to metal-foil transducers, piezoresistive transducers are more sensitive and linear, but have large temperature dependence and large initial offsets.

In principle, all strain gauges react to an applied force by varying a resistance value. Therefore, in the presence of electrical excitation they effectively convert a pressure or weight to an electrical signal. Usually one, two, or four of these active resistive elements (strain gauges) are arranged in a Wheatstone bridge configuration (sometimes called a load cell) to produce a differential output voltage in response to pressure or weight.

Engineers can design a sensor module that meets the unique requirements of diverse force-sensing applications. A successful design would include the suitable sensing element for the physical property and an appropriately designed signal chain.



Block diagram of the signal chain in a force-sense application. For a list of Maxim's recommended pressure-sensor solutions, please go to: www.maxim-ic.com/psi.

Complete Signal-Chain Solutions

The sensor signal chain must handle extremely small signals in the presence of noise. Accurately measuring changes in the output voltage from a resistive transducer requires circuitry that provides the following electrical functions: excitation, amplification, linearization, offset nulling, filtering, and acquisition. Some solutions may also require the use of digital signal processing (DSP) techniques for signal manipulation, error compensation, gain, filtering, and user programmability.

Discrete vs. Integrated Solutions

In this chapter we discuss functional blocks, keeping in mind that Maxim offers more highly integrated solutions when the application warrants their use. Some examples are given.

Excitation

Accurate and stable voltage or current sources with low-temperature drift are required for sensor excitation. To easily eliminate effects of reference voltage tolerance, it is common practice to use the same reference for both the sensor excitation and the analog-to-digital converter (ADC). This makes the signals ratiometric, eliminating first-order tolerances allowing the use of less accurate references, or alternately providing higher performance from a given reference.

Amplification and Level Translation—the Analog Front-End (AFE)

In some designs the transducer's output voltage range will be very small, with the required resolution reaching the nanovolt range. In such cases, the transducer's output signal must be amplified before it is applied to the ADC's inputs. To prevent this amplification step from introducing errors, low-noise amplifiers (LNAs) with extremely low offset voltage (V_{OS}) and low temperature and offset drifts must be selected. A drawback of Wheatstone bridges is that the common-mode voltage is much larger than the signal of interest. This means that the LNAs must also have excellent common-mode rejection ratios (CMRR), generally greater than 100dB.

When single-ended ADCs are used, additional circuitry is required to remove large common-mode voltages before acquisition. Additionally, since the signal bandwidth is low, the 1/f noise of the amplifiers can introduce errors. Chopper-stabilized amplifiers are, therefore, often used. Some of these stringent amplifier requirements can be avoided by using a small portion of the full-scale range of a very high-resolution ADC.

Acquisition—the ADC

When choosing the ADC, look at specifications like noise-free range or effective resolution that indicate how well an ADC can distinguish a fixed input level. Alternate phrasing for these applications might be noise-free counts or codes inside the range. Most high-accuracy ADC data sheets show these specifications as a table of peak-to-peak noise or RMS noise vs. speed; sometimes the specifications are shown graphically as noise histogram plots.

Other ADC considerations include low offset error, low temperature drift, and good linearity. For certain low-power applications, speed vs. power is an important criterion.

Filtering

The bandwidth of the transducer signal is generally small and the sensitivity to noise is high. It is, therefore, useful to limit the signal bandwidth by filtering to reduce the total noise. Using a sigma-delta ADC can simplify the noise-filtering requirement because of the inherent shaping of the noise spectrum out of the band of interest by the oversampling in that architecture.

Digital Signal Processing (DSP)—the Digital Domain

Besides the analog signal processing, the captured signals are further processed in the digital domain for signal extraction and noise reduction. It is common to find focused algorithms that cater to particular applications and their nuances. There are also generic techniques, such as offset and gain correction, linearization, digital filtering, and temperature (and other dependent factors)-based compensation that are usually applied in the digital domain. The DSP function necessitates sufficient processing capability in the signal path.

Integrated Solution

In more highly integrated solutions, all required functional blocks are integrated into a single IC commonly called a sensor signal conditioner. A sensor signal conditioner is an application-specific IC (ASIC) that performs compensation, amplification, and calibration of the input signal, normally over a range of temperatures. Depending on the sophistication of the signal conditioner, the ASIC integrates some or all of the following blocks: sensor, sensor excitation circuitry, digital-to-analog converter (DAC), programmable gain amplifier (PGA), ADC, memory, multiplexer (mux), CPU, temperature sensor, and digital interface.

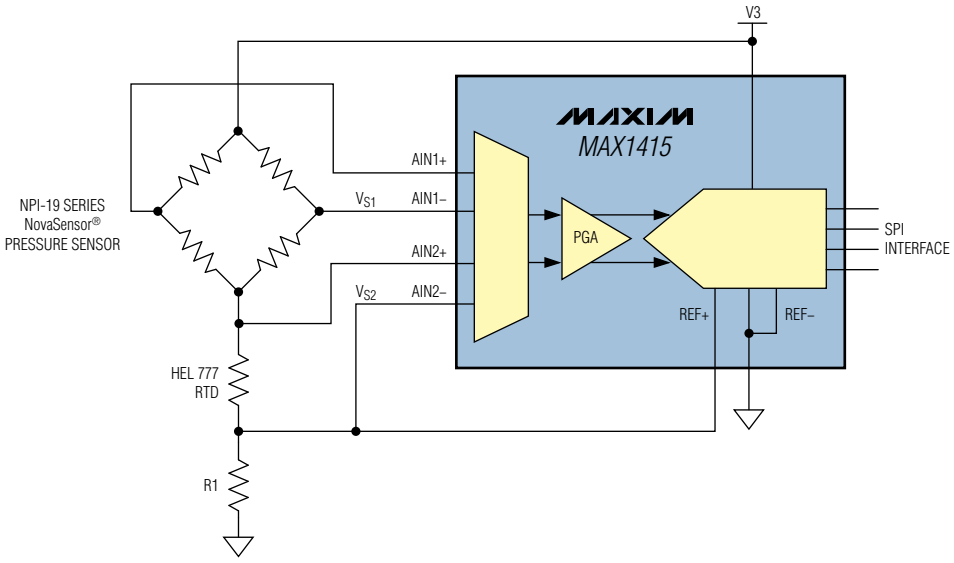
There are two types of sensor signal conditioners: analog signal-path conditioners and digital signal-path conditioners. Analog signal conditioners have a faster response time and provide a continuous-output signal, immediately reflecting changes at the input. They generally have a hardwired (inflexible) compensation scheme. Digital conditioners, which are usually microcontroller-based, have slower response times because of latencies introduced by the ADC and DSP routines, and they introduce quantization error in the output signal. The magnitude of the quantization error depends on the resolution of the ADC used and on the resolution of data processed within the microprocessor. The main benefits of digital signal conditioners are the flexibility of the compensation algorithms that can be adapted to the user's application, and the ease with which the output can be interfaced to an external microcontroller. Maxim offers both fully analog path and digital signal-path conditioners.

www.maxim-ic.com/psi

Flexible ADCs Interface with a Wide Range of Sensor Signal Levels

MAX1415/MAX1416

Pressure sensors commonly have high sensitivity to temperature. Therefore, a pressure sensor circuit should monitor temperature as well as the output of the pressure sensor. The MAX1415/MAX1416 feature two differential inputs that allow measurement of both pressure and temperature (using a resistance temperature detector, RTD). Differential reference inputs allow ratiometric measurement of the 3V excitation voltage. The MAX1415 requires a single 2.7V to 3.6V supply, and the MAX1416 requires a single 4.75V to 5.25V supply.



Flexible MAX1415 ADC interfaces with pressure and temperature sensors.

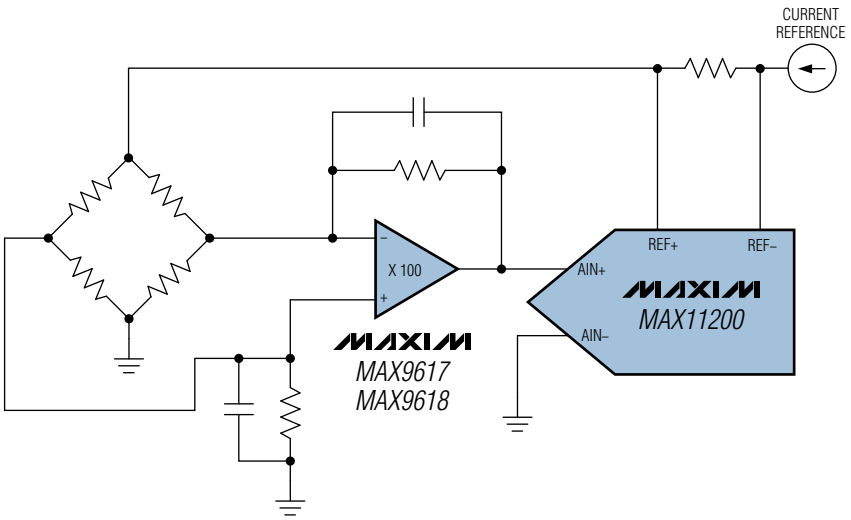
Benefits

- Match a wide range of sensor signal levels
  - On-chip PGA allows as low as 20mV full-scale range (FSR) to match sensor output
- Feature integration reduces design complexity
  - Built-in self- and system-calibration modes improve accuracy and shorten design time
  - Built-in digital filter for 50Hz/60Hz rejection removes unwanted powerline interference
- Simplify multichannel ratiometric/ bridge-type designs
  - Differential reference input for ratiometric measurement common to bridge-type circuits
  - Two differential channels measure pressure and temperature

Maintain High Accuracy Over Time and Temperature

MAX9617/MAX9618, MAX11200

One of the biggest challenges when interfacing to sensors is dealing with the low signal levels. Since the signal bandwidth (BW) lies in the low hertz range for many sensors, the 1/f noise of op amps is an important factor. Maxim's MAX9617/MAX9618 low-power (< 100µA) autozero op amps offer the industry's lowest noise (42nV/√Hz) operation. These devices have the best-in-class peak-to-peak noise of < 420nV$_{P-P}$ for 0.1Hz to 10Hz BW. Coupling these op amps with the MAX11200, the industry's leading low-powered, 24-bit (21 noise-free bits), sigma-delta ADC, creates an ideal solution for capturing low-frequency, low-amplitude signals accurately.



Circuit using the MAX9617/MAX9618 op amps and the MAX11200 ADC achieves high accuracy over time and temperature.

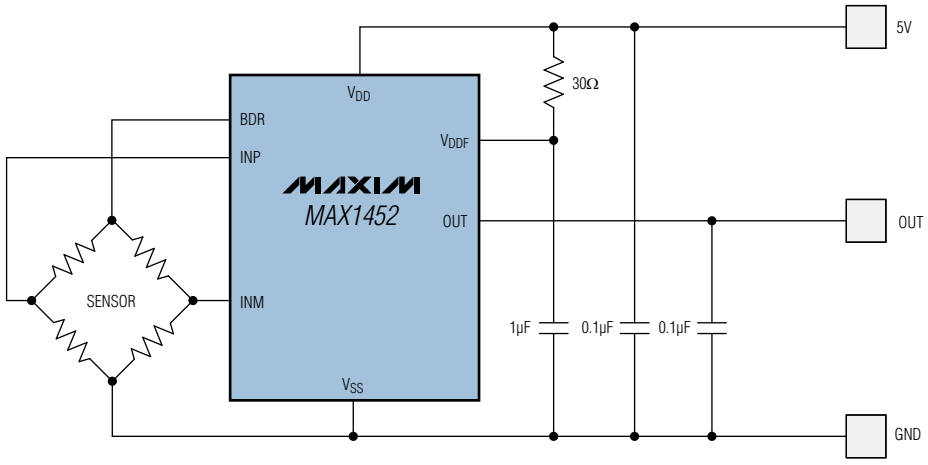
Benefits

- Minimize system errors over time and temperature
  - Autozero op-amp technology reduces TCV$_{OS}$ to 120nV/°C
- Provide the most accurate measurements at the lowest power
  - Highest resolution per-unit-power ADC for sensors on a 4–20mA loop: 21 bits of noise-free range at 10sps drawing close to 200µA
- Simple two-chip solution maximizes dynamic range and resolution
  - 21 bits of noise-free range identify signals down to 500nV steps for wide-range, high-accuracy sensor applications
  - Industry's lowest noise, autozero op amp (< 420nV$_{P-P}$ noise from 0.1Hz to 10Hz)
  - No 1/f component ensures low distortion below 0.1Hz in the signal-conditioning stage

Low-Cost, High-Precision Analog Sensor Signal Conditioner Simplifies Sensor Design

MAX1452

The MAX1452 is a versatile analog sensor signal conditioner that accepts output from all types of resistive elements. Its fully analog signal path enables fast response and provides current or voltage excitation for optimal design flexibility. Four integrated 16-bit DACs and a PGA provide high-resolution input compensation, amplification, and calibration. The MAX1452 includes on-chip flash memory and a temperature sensor that performs multipoint temperature compensation for accurate readings.



Low-cost, high-precision MAX1452 sensor signal conditioner in a ratiometric configuration.

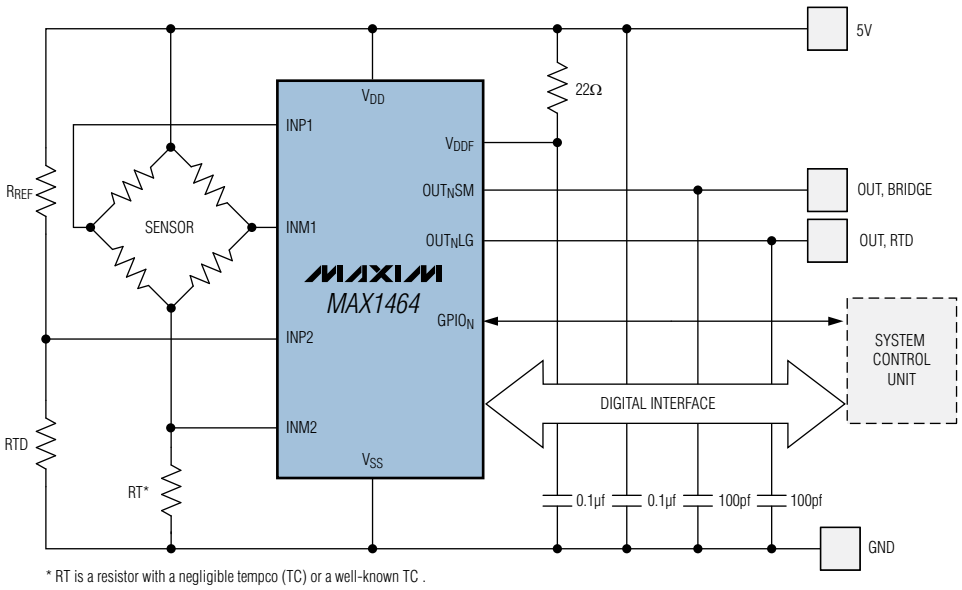
Benefits

- Reduces bill of materials (BOM) cost
  - High integration minimizes external components
  - No external trim components required to produce calibrated, accurate output
- Removes all systematic errors for a highly accurate output
  - Fully analog signal path provides a continuous output with no quantization error
  - Four 16-bit DACs (76µV resolution) provide precise compensation of full-span output (FSO) and offset
  - Temperature compensation allows calibration that approaches the repeatability of the input signal
- Reduces product development time and inventory complexity due to programmability
  - Suitable for use with many types of transducers and in multiple applications
  - Using same signal conditioner in many applications allows reuse of the application circuit
  - Can be used in products requiring voltage output or 4–20mA current loop

Low-Power, Low-Noise, Multichannel Digital Sensor Signal Conditioner Saves Cost and Board Space

MAX1464

The MAX1464 is a highly integrated, digital, multichannel sensor signal conditioner optimized for industrial process-control and automotive applications. Typical implementations include pressure sensing, RTD and thermocouple linearization, weight sensing/classification, and remote process monitoring with limit indication. The MAX1464 simplifies designs and improves manufacturing efficiency by accepting sensors with either single-ended or differential outputs. It provides comprehensive temperature compensation without requiring any external trim components. A calibrated output signal can be driven independently through an SPI-compatible interface, voltage-output DACs, or PWM outputs. The MAX1464 integrates a 16-bit CPU, 128 bytes for user-programmable flash memory, and two general-purpose inputs/outputs (GPIOs). It has a flexible dual op-amp output block and supports 4–20mA current loop applications.



The MAX1464 multichannel digital signal conditioner measures one differential and two single-ended inputs.

Benefits

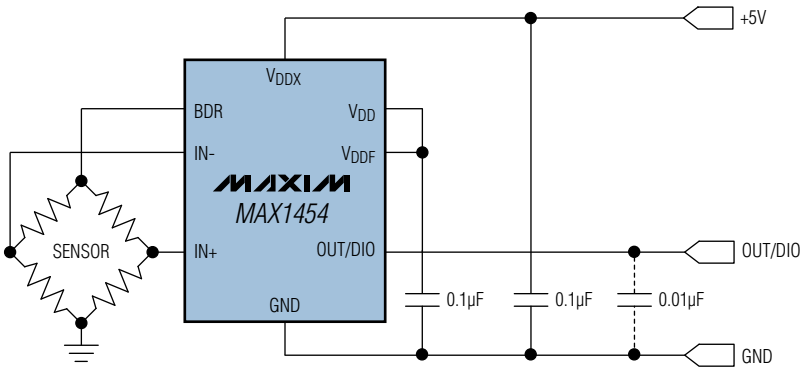
- Multichannel functionality reduces BOM cost, improves performance, and saves space
  - Use one multichannel device for lower cost and better measurement matching compared with multiple devices
  - Highly integrated conditioner minimizes component requirements, saving board space
  - No external trim components required for a calibrated and accurate output
- Adaptable compensation algorithm optimizes sensor performance
  - Algorithm can be customized for the application
  - Compensation algorithm is stored in on-chip nonvolatile flash memory
- Reduces product development time
  - Flexible for use in products requiring digital output, voltage output, PWM output, or a 4–20mA current loop
  - Integrated microprocessor with only 16 instructions makes programming easy
  - Suitable for use with many types of transducers

High-Performance Sensor Signal Conditioner with Fully Analog Signal Path

MAX1454

The MAX1454 is a high-performance, robust, reliable, and highly integrated sensor signal conditioner. The fully analog signal path provides amplification, calibration, and temperature compensation of the input signal while introducing no quantization noise to the signal. Offset and span are calibrated with integrated 16-bit DACs, allowing sensors to be truly interchangeable. Features such as 45V over/reverse voltage protection, output current limiting, and input sensor fault detection enable development of robust and reliable products.

The MAX1454 architecture includes programmable sensor excitation, a 32-step PGA, 2K x 8 bits internal flash memory, four 16-bit DACs, and an on-chip temperature sensor. In addition to offset and span compensation, the device provides a unique temperature-compensation method for offset TC and FSO TC to offer a remarkable degree of flexibility while minimizing manufacturing costs. The device is packaged in a 16-pin TSSOP package and can operate over the -40°C to +125°C extended temperature range.



The MAX1454 signal conditioner uses a fully analog signal path to avoid quantization noise.

Benefits

- Integration provides high accuracy with reduced BOM cost
  - Four 16-bit DACs (76µV resolution) provide accurate compensation of FSO and offset
  - Multitemperature compensation allows sensor calibration that approaches repeatability of the input signal
  - Highly integrated—requires no external trim components to produce calibrated and accurate output
  - Simple 3-wire (V_{DDX}, GND, OUT/DIO) sensor connection
- Improves system robustness and reliability
  - 45V over/reverse voltage protection protects against power surges and operator error
  - Output current limit protects against unintentional shorting of the output pin to supply or ground
  - Input fault detection provides warning of bad sensor and allows for preventive/protective action
- Simplifies sensor selection by accommodating wide range of sensors
  - Operates with wide supply range (3V to 5.5V)
  - Accepts wide range of sensor sensitivity (1mV/V to 200mV/V)

Temperature Sensing

Overview

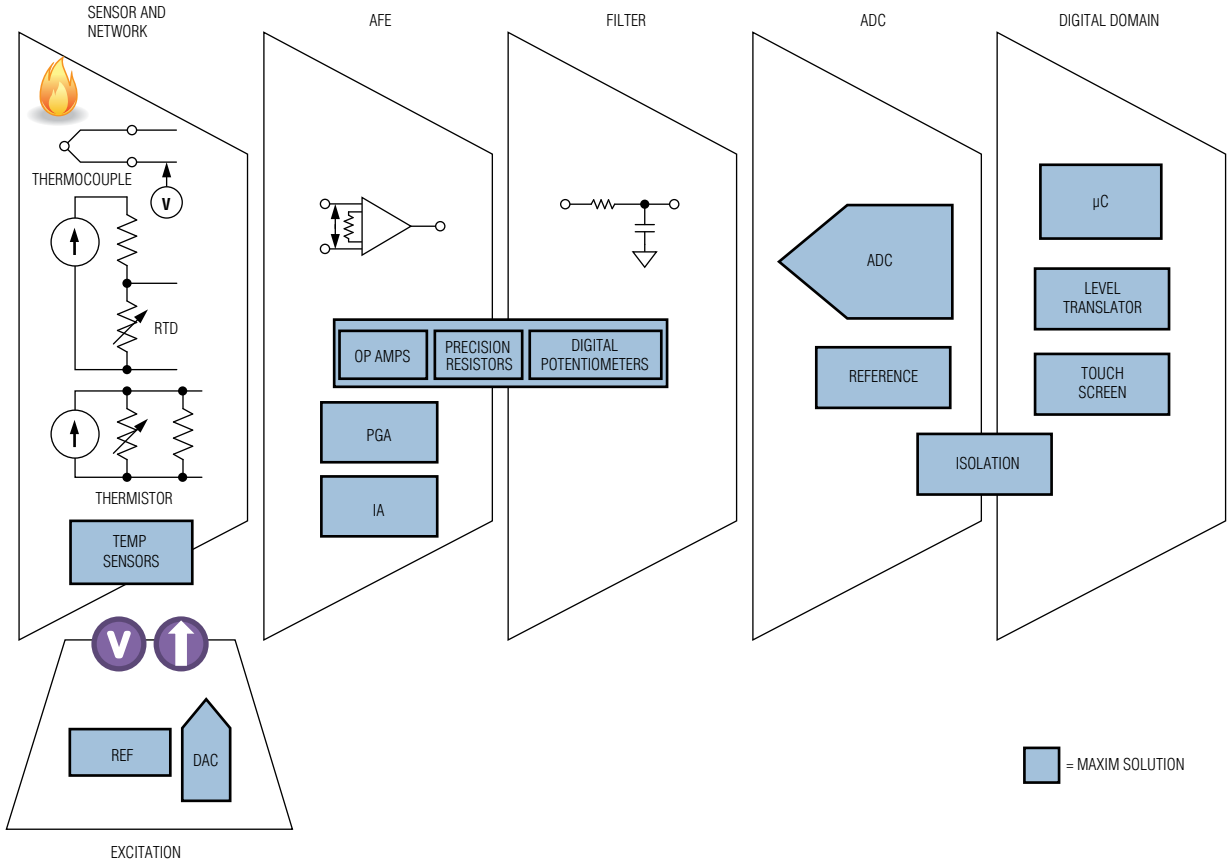
Temperature sensing is critically important for implementing three key functions in industrial systems.

1. **Temperature control,** for example in ovens, refrigeration, and environmental-control systems, depends on the measurement of temperature to make heating/cooling decisions.
2. **Calibration** of a variety of transducers, oscillators, and other components often varies with temperature. Therefore, temperature must be measured to ensure the accuracy of sensitive system components.

3. **Protection** of components and systems from damaging temperature excursions. Temperature sensing determines the appropriate action to take.

Thermistors, RTDs, thermocouples, and ICs are some of today's most widely used temperature-sensing technologies. Each design approach has its own strengths (e.g., cost, accuracy, temperature range) that make it appropriate for specific applications. Each of these technologies will be discussed.

In addition to the industry's most comprehensive line of dedicated temperature-sensor ICs, Maxim manufactures all the components necessary to interface a system to thermistors, RTDs, and thermocouples.



Block diagram of the signal chain in a temperature-sensing application. For a list of Maxim's recommended temperature-sensor solutions, please go to: www.maxim-ic.com/-40+85.

Thermistors

Thermistors are temperature-dependent resistors, usually made from semiconducting materials like metal-oxide ceramics or polymers. The most widely used thermistors have a negative temperature coefficient of resistance and, therefore, are often referred to as NTCs. There are also positive temperature coefficient (PTC) thermistors.

Thermistor characteristics include a moderate temperature range generally up to +150°C, although some are capable of much higher temperatures; low-to-moderate cost depending on accuracy; and poor, but predictable linearity. Thermistors are available in probes, in surface-mount packages, with bare leads, and in a variety of specialized packages. Maxim also manufactures ICs that convert thermistor resistance to a digital format.

A thermistor is often connected to one or more fixed-value resistors to create a voltage-divider. The output of the divider is typically digitized by an ADC. The thermistor's nonlinearity can be corrected either by a lookup table or by calculation.

RTDs

Resistance temperature detectors (RTDs) are resistors whose resistance varies with temperature. Platinum is the most common, most accurate wire material. Platinum RTDs are referred to as Pt-RTDs. Nickel, copper, and other metals can also be used to make RTDs.

RTD characteristics include a wide temperature range up to +750°C, excellent accuracy and repeatability, and reasonable linearity. For Pt-RTDs, the most common values for nominal resistance at 0°C are 100Ω and 1kΩ, although other values are available.

Signal conditioning for an RTD can be as simple as combining the RTD with a precision, fixed resistor to create a voltage-divider, or it can be more complex, especially for wide-range temperature measurements. A common approach consists of a precision current source, a voltage reference, and a high-resolution ADC, as shown in **Figure 1**. Linearization can be performed with a lookup table, through calculation, or by external linear circuits.

Thermocouples

Thermocouples are made by joining two wires of dissimilar metals. The point of contact between the wires generates a voltage that is approximately proportional to temperature. There are several thermocouple types that are designated by letters. The most popular is the K type.

Thermocouple characteristics include a wide temperature range up to +1800°C; low cost, depending on the package; very low-output voltage of about 40µV per °C for a K-type device; reasonable linearity; and moderately complex signal conditioning, i.e., cold-junction compensation and amplification.

Measuring temperature with a thermocouple is somewhat difficult because the thermocouple's output is low. Measurement is further complicated because additional thermocouples are created where the thermocouple wires contact the copper wires (or traces) that connect to the signal-conditioning circuitry. This contact point is called the cold junction (see **Figure 2**). To accurately measure temperature with a thermocouple, a second temperature sensor must be added at the cold junction, as shown in **Figure 3**. Then the temperature measured at the cold junction is added to the value indicated by the measurement of the thermocouple voltage. The example circuit in Figure 3 shows one implementation, which includes a number of precision components.

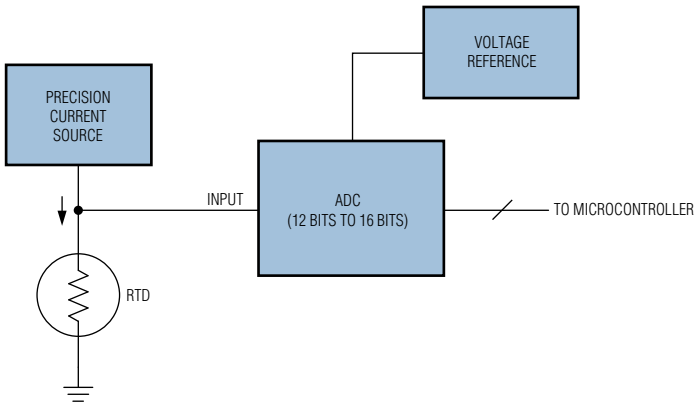


Figure 1. Simplified RTD signal-conditioning circuit.

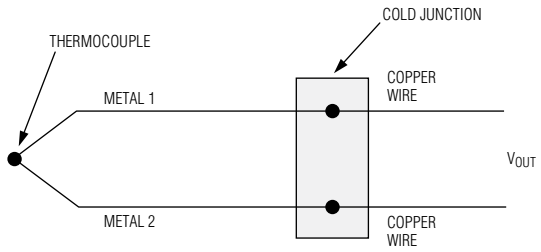


Figure 2. Simple thermocouple circuit. The junction between metal 1 and metal 2 is the main thermocouple junction. Other thermocouples are present where the metal 1 and metal 2 wires join with the measuring device's copper wires or PCB traces.

In addition to all the components shown in Figure 3, Maxim manufactures the MAX31855 family of thermocouple-to-digital converters, which perform the signal-conditioning functions for J-, K-, R-, S-, T-, and E-type thermocouples. These devices simplify the design task and significantly reduce the number of components required to amplify, cold-junction compensate, and digitize the thermocouple's output. For more information, refer to Reference Design 5032 at: www.maxim-ic.com/AN5032.

Temperature-Sensor ICs

Temperature-sensor ICs take advantage of the linear and predictable thermal characteristics of silicon PN junctions. Because they are active circuits built using conventional semiconductor processes, these ICs take a variety of forms. They include many features such as digital interfaces, ADC inputs, and fan-control functions that are not available in other technologies. The operating temperature range for temperature-sensor ICs extends as low as -55°C and as high as +125°C, with a few products operating to an upper limit of around +150°C. Descriptions of common types of temperature-sensor ICs follow.

Analog Temperature Sensors

Analog temperature-sensor ICs convert temperature to voltage or, in some cases, to current. The simplest voltage-output analog temperature sensors have just three active connections: ground, power-supply voltage input, and output. Other analog sensors with enhanced features have additional inputs or outputs, for example, comparator or voltage-reference outputs.

Analog temperature sensors use the thermal characteristics of bipolar transistors to develop an output voltage that is proportional to temperature. Gain and offset are applied to this voltage to provide a convenient relationship between the sensor's output voltage and the die temperature. Temperature accuracy can be excellent. The DS600, for example, is the industry's most accurate analog temperature sensor, with guaranteed error less than ±0.5°C from -20°C to +100°C.

Local Digital Temperature Sensors

Integrating an analog temperature sensor with an ADC is an obvious way to create a temperature sensor with a direct digital interface. Such a device is normally called a digital temperature sensor or a local digital temperature sensor. "Local" indicates that the sensor measures its own temperature. This operation contrasts with a remote sensor that measures the temperature of an external IC or a discrete transistor.

Basic digital temperature sensors simply measure temperature and allow the temperature data to be read by a number of interfaces including SPI/3-wire, I^2C, 1-Wire, and PWM. More complex digital sensors offer other features, such as over/undertemperature outputs, registers to set trip thresholds for these outputs, and EEPROM. Maxim manufactures several local digital temperature sensors, including the DS7505 and DS18B20 that guarantee accuracy of ±0.5°C over a wide temperature range.

Remote Digital Temperature Sensors

A remote digital temperature sensor is also called a remote sensor or a thermal diode sensor. The remote sensor measures the temperature of an external transistor, either a discrete transistor

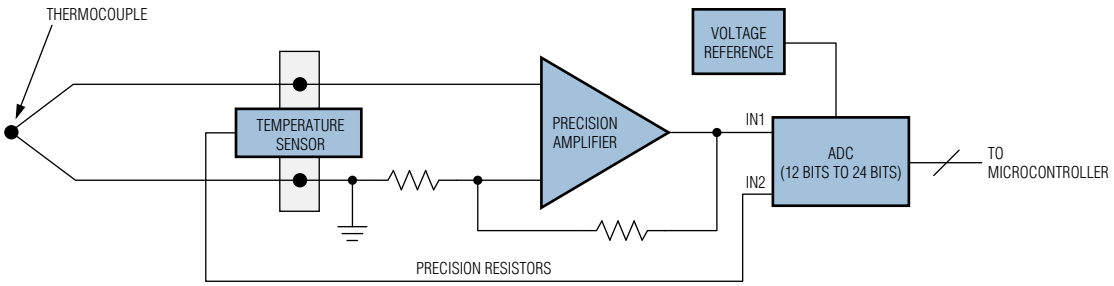


Figure 3. Example of a thermocouple signal-conditioning circuit.

or one that is integrated on the die of another IC. Microprocessors, field-programmable gate arrays (FPGAs), and ASICs often include one or more sensing transistors, usually called thermal diodes, similar to the one shown in **Figure 4**.

There is an important advantage to remote temperature sensors: they allow you to monitor more than one hot spot with a single IC. A basic single remote sensor like the MAX6642 in Figure 4 can monitor two temperatures: its own and an external temperature. The external location can be on the die of a target IC, or a hot spot on a board that it monitors with a discrete transistor. Some remote sensors monitor as many as seven external temperatures. Thus, eight locations, consisting of ICs and board hot spots, are monitored from a single chip.

Consider the MAX6602 as an example. This temperature sensor has four remote diode inputs so it can monitor the temperatures of a pair of FPGAs with integrated thermal diodes, two board hot spots using discrete transistors, and the temperature of the board at the MAX6602's location. Both the MAX6602 and the MAX6642 achieve ±1°C accuracy when reading external thermal diodes.

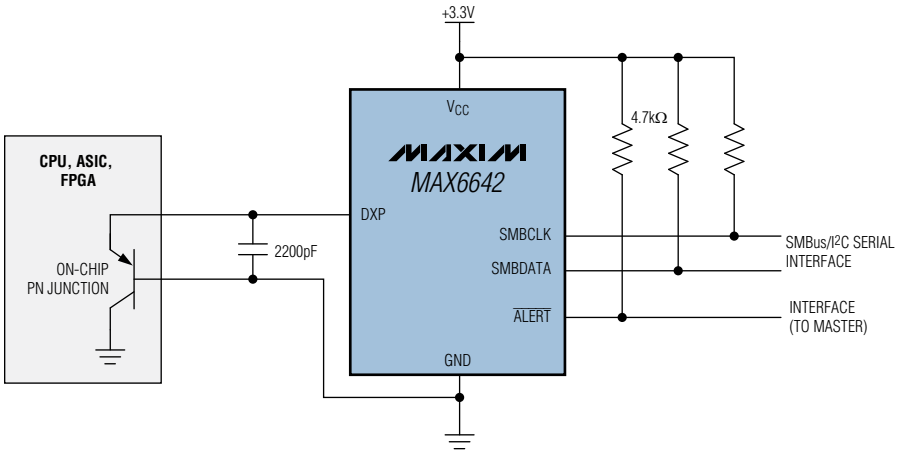


Figure 4. A remote temperature sensor, the MAX6642, monitors the temperature of a sensing transistor (or thermal diode) on the die of an external IC.

www.maxim-ic.com/-40+85

Simple, Integrated RTD-to-Digital Conversion

MAX1402, MAX4236/MAX4237

Any appreciable resistance in the RTD's leads will cause errors in temperature measurement. Therefore, for long wire lengths use a 3- or 4-wire connection to eliminate lead-resistance errors. The circuit in **Figure 1** is a 4-wire RTD interface using the MAX1402 over-sampling ADC. The MAX1402 has two matched current sources, which significantly reduce the IC count in an RTD converter. One of the current sources provides excitation current for the RTD, in this case, a PT100. Because the excitation current does not flow through the sense leads, lead resistance will not affect the temperature-measurement accuracy. The second current source drives a precision resistor to generate the reference voltage for the ADC, thereby eliminating the need for an external voltage reference.

For best accuracy when using an RTD, apply linearity correction to the acquired data to compensate for the PT100's nonlinearity. Also use gain correction to compensate for both the tolerance of the reference resistor and mismatch between the current sources.

The digital linearity correction can be avoided if a small amount of positive feedback is applied to an amplifier circuit, as shown in **Figure 2**. The resulting linearity error from -100°C to +200°C is less than ±0.05°C. This circuit does not compensate for long leads, so it should be used when the RTD is located near the measurement circuitry. For more details, refer to Maxim's Application Note 3450: "Positive Analog Feedback Compensates PT100 Transducer."

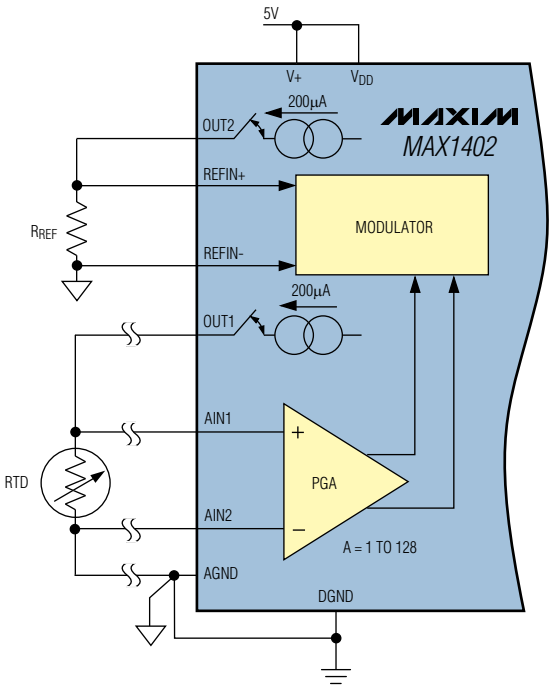


Figure 1. Circuit diagram shows the MAX1402 ADC in a 4-wire interface for a PT100 RTD.

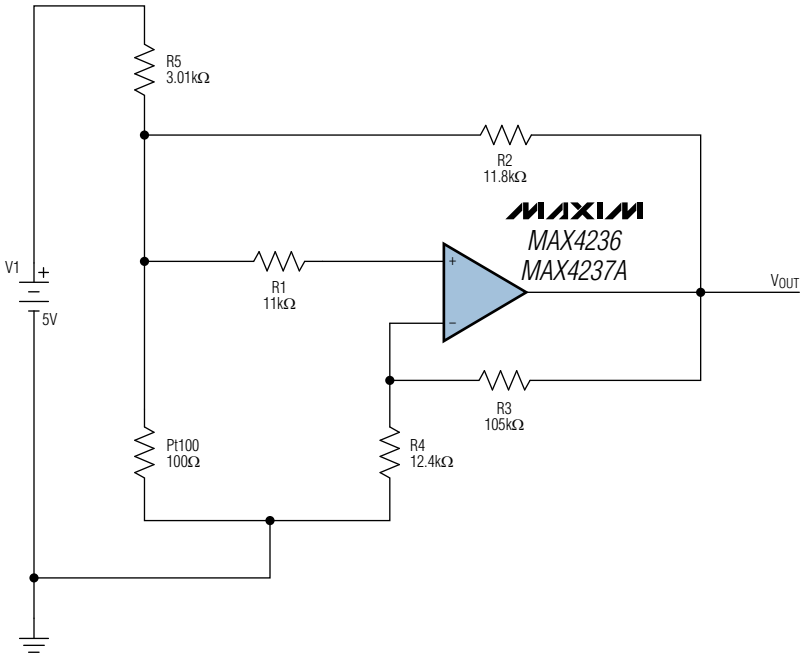


Figure 2. A PT100 linearizer circuit. PT100 is compensated by one additional resistor. R2 provides a small positive feedback.

Complete Thermocouple Interface Designs Eliminate External Components, Use Less Space

DS600, MAX1416, MAX6133, MAX31855

The thermocouple circuit shown in **Figure 1** uses the MAX1416 ADC that allows direct interfacing with thermocouples, thereby eliminating external components and reducing the overall footprint. The internal PGA eliminates the need for an external precision amplifier; self-calibration avoids expensive calibration procedures during manufacture. The MAX1416 accommodates negative temperatures because its input common-mode range extends 30mV below ground.

Cold-junction temperature is measured using a DS600 analog temperature sensor located at the thermocouple connector. With ±0.5°C accuracy, the DS600 provides the most accurate cold-junction compensation of any analog temperature-sensor IC on the market. Adding the cold-junction temperature to the temperature measured by the ADC corrects for the parasitic thermocouples created when the thermocouple connector is linked to the system.

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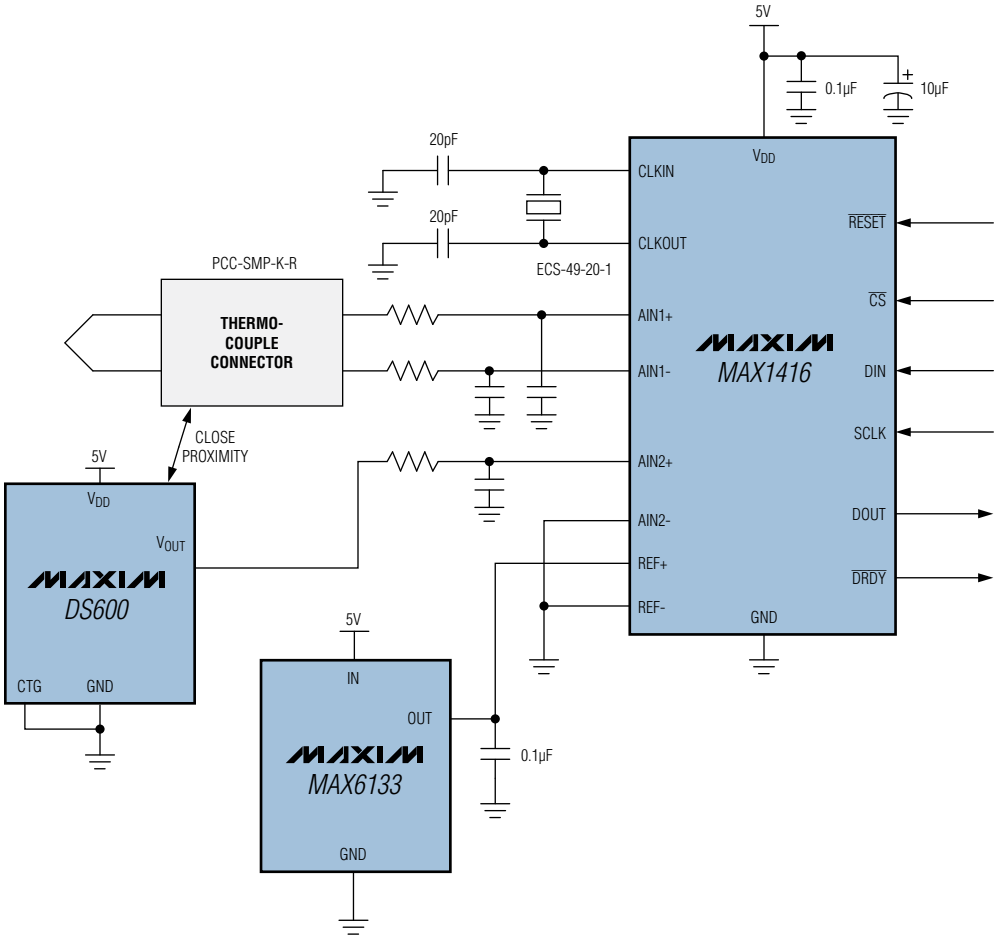


Figure 1. A thermocouple measurement circuit in which the MAX1416 measures the thermocouple output and the DS600 measures the cold-junction temperature.

Complete Thermocouple Interface Designs Eliminate External Components, Use Less Space (continued)

DS600, MAX1416, MAX6133, MAX31855

Figure 2 shows a fully integrated thermocouple circuit using the MAX31855 thermocouple-to-digital converter. With the ADC, reference, gain, and cold-junction compensation all integrated, the MAX31855 measures positive and negative temperature values from a K-type thermocouple and requires no external components.

Versions are available for use with J-, K-, R-, S-, T-, and E-type thermocouples. Thus, using the MAX31855 reduces part count, design time, and system complexity. The maximum measured temperature is +1024.75°C. The 12-bit resolution results in an LSB value of 0.25°C. In addition to sensing thermocouple temperature, the MAX31855 detects open circuits and shorts to ground or supply.

For more information on temperature sensing, refer to Maxim's Thermal Management Handbook at: www.maxim-ic.com/thermal-handbook.

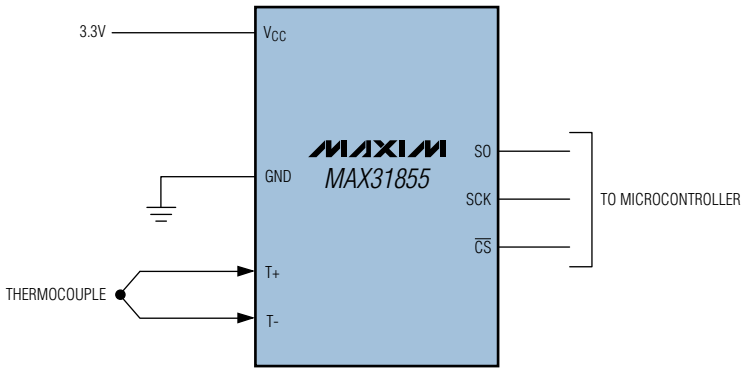


Figure 2. The MAX31855 is a complete thermocouple-to-digital converter for K-type thermocouples.

Light Sensing

Overview

Light sensing is used in a variety of applications ranging from light dimming based on ambient light intensity to sophisticated industrial process-control applications where critical decisions are based on the sensor's output. Light may be sensed to monitor light intensity, to use light in a feedback loop, or to use light as a signal itself as in indicators, traffic signals, etc.

The main benefit of using a light sensor in a control loop is to provide immunity against harsh environmental conditions. Since light is not sensitive to vibration, magnetic field, or humidity, it provides robust readings.

A mainstream type of light sensor is an ambient light sensor that measures the amount of visible light in an environment. An ambient light sensor should have a signal spectrum that exactly matches the human eye response, centered around 555nm, which corresponds to green. Since light intensities in the ambient environment can vary over a broad range, a light sensor with wide dynamic range can be a key requirement.

For more specialized applications, consider using a light sensor that measures more than just the visible spectrum and gives separate results for different bands of wavelengths. For these applications, an RGB color sensor is a good solution. In some cases, other wavelengths, including infrared (IR), may be of interest. Maxim's MAX44006/8* RGB-clear-IR products measure light over a broad spectrum ranging from 400nm up to 1000nm (near-ultra violet to near-infrared).

To enhance the reliability and accuracy of the measurements, using digital light sensors can provide many benefits—including reduced board area, improved noise performance, better sensitivity, and lower cost—when compared with discrete and analog solutions.

False readings in light measurements can be caused by 50/60Hz flicker noise and DC IR noise. Well-designed digital light sensors can overcome these issues in their digital filtering sections.

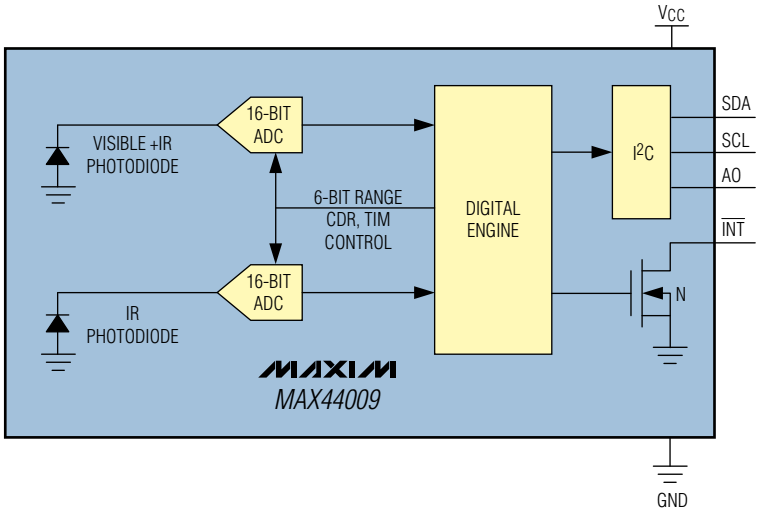
Moreover, digital light sensors with functions like interrupt and persistence help to reduce the overhead on microprocessors, allowing the system to respond faster and consume less power.

*Future product—contact the factory for availability.

Save Power, Reduce System Cost and Complexity with an Integrated Ambient Light Sensor

MAX44009

The MAX44009 is a highly integrated ambient light sensor with a digital output. Its 1µA current consumption saves power in the system. The integrated ADC and an I^2C communication channel reduce cost by eliminating external components. Space is also conserved, as this integrated solution has a 2mm x 2mm footprint. The added functionality of an adaptive gain block makes it easier to integrate this component into a system.



Typical operating circuit for the 22-bit MAX44009 integrated ambient light sensor.

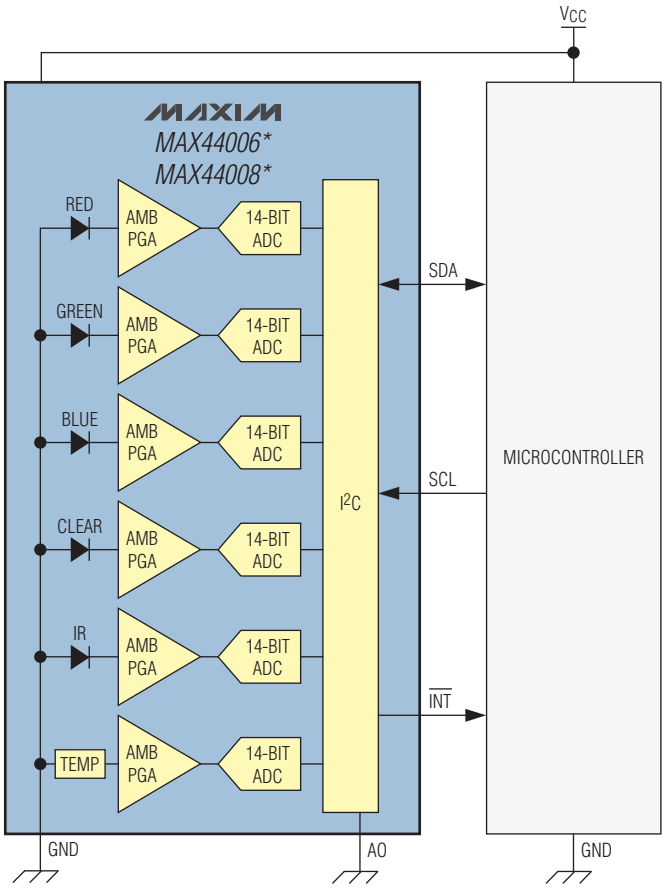
Benefits

- Minimizes power requirements
  - Ultra-low 1µA operating current consumption
  - V_{CC} is 1.7V to 3.6V and eliminates the need for different supply rails
- Adaptable for a wide variety of applications
  - Wide 0.03lx to 130,000lx sense range
  - Adjustable conversion time provides flexibility
- High integration simplifies system design
  - 6-bit adaptive gain control for autoranging reduces design complexity
  - Optical filters provide an optical response similar to the human eye, and block IR and UV light

Optical Fusion—RGB-IR-Ambient and Temperature Sensing

MAX44006/MAX44008**

The MAX44006/MAX44008 integrate five optical sensors in each of two products: red, green, blue (RGB) sensors; an ambient light (clear) sensor; and an ambient infrared sensor with an I²C interface. These sensors include five parallel ADCs to provide faster and noise-immune measurements. These highly integrated optical sensors also include a temperature sensor to improve reliability and performance.



The MAX44006 and MAX44008 measure intensity of RGB, IR, and visible light.

Benefits

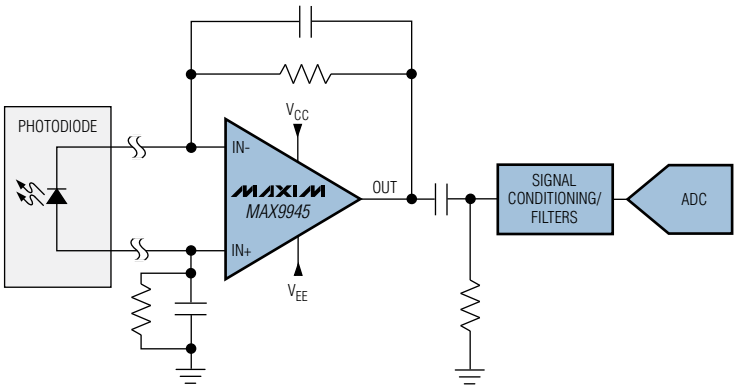
- Optical-thermal fusion provides multiband performance in a small footprint
  - 6 sensors (5 optical + 1 thermal) in parallel
  - 1.5ms to 100ms ADC integration time offers speed vs. resolution flexibility
  - Tiny 2mm x 2mm x 0.6mm package
- Reliable measurements over a wide range of environmental conditions
  - 50/60Hz immunity for robust readings
  - IR rejection for RGB sensors provides high-performance RGB reading
  - Front-end temperature compensation for reliable measurements
- High-level integration reduces time to market
  - Integrated interrupt and persist features off-load work from microcontroller
  - I²C digital communication provides noise-immunity at the interface
  - 1.8V to 5.5V wide supply voltage range is easy to interface wide range of microcontrollers

*Future product—contact the factory for availability.

Maximize System Accuracy in Photodiode and High-Ohmic Sensor Applications

MAX9945

The MAX9945 operational amplifier features an excellent combination of low-operating power and low-input-voltage noise. MOS inputs enable the MAX9945 to feature low 50fA input-bias currents and low (15nV/√Hz) input-current noise. The MAX9945 simplifies the interface between high-ohmic sensors or low-current TIA applications.



Highly accurate light-sensor interface features the MAX9945 op amp.

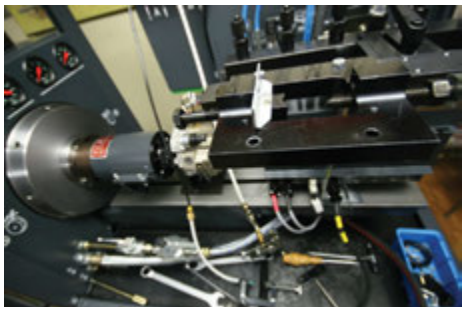
For more information on Maxim's optical communication products, please go to: www.maxim-ic.com/fiber.

Benefits

- Improves system's signal-to-noise ratio (SNR) for more accurate measurements
  - 50fA low input-bias current
  - 1fA/√Hz low input-current noise
  - 15nV/√Hz low noise
- High-voltage robust design simplifies mixed-voltage designs
  - 4.75V to 38V single-supply voltage range
  - ±2.4V to ±19V dual-supply voltage range
  - Rail-to-rail output-voltage swing

Proximity Sensing

Overview



Proximity sensing is used in many applications to control position, to sense an object, and to control speed. It can be achieved by sensing a magnetic field or light.

Using light for proximity sensing is a good way to isolate components from the environment and from each other. Infrared (IR) light is usually used for this purpose. In addition, digital IR proximity sensors can be employed to sync the transmitter and receiver, thereby rejecting noise from DC IR sources. Maxim's MAX44000 is a good example of using an IR LED to sense the proximity of an object. It pulses the LED at a low duty cycle, reducing heat dissipation and eliminating problems due to detection of sunlight.

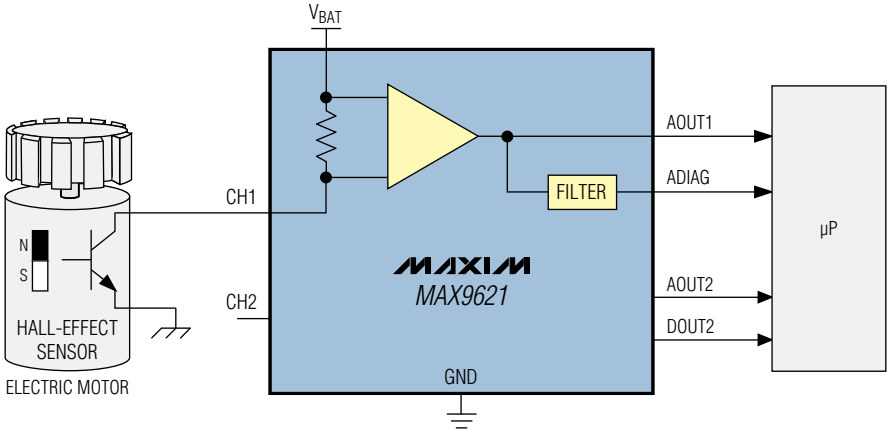
Hall-effect sensors are also used for proximity sensing. The Hall effect is the production of a voltage across a current-carrying conductor in the vicinity of a magnetic field. Sensors based on this principle detect a change in the magnetic field, thus allowing speed, position, and direction to be deduced. This signal can then be digitized for control purposes. The robustness and reliability of Hall-effect sensors have proven valuable in many industrial applications.

Diagnostics and protection are crucial elements of Hall-effect sensor interface electronics. Maxim's MAX9921/MAX9621 Hall-effect sensor interface products combine dual Hall-effect sensor connectivity with diagnostics and protection features to improve the reliability of Hall-effect sensors in position-sensing applications.

Reliable Hall-Effect Sensor Interface Provides Flexibility and Reduces Component Count

MAX9621

The MAX9621 provides a single-chip solution to interface two 2-wire Hall-effect sensors to low-voltage microprocessors (µP) through either a digital output for Hall-effect switches or an analog output for linear information, or both. The MAX9621 protects the Hall-effect sensors from supply transients up to 60V at the BAT supply. Normal operating supply voltage ranges from 5.5V to 18V. If the BAT supply rises above 18V, the MAX9621 shuts off the current to the Hall-effect sensors. When a short-to-ground fault condition is detected, the current to the Hall-effect input is shut off and the condition is indicated at the analog output by a zero-current level and a high digital output.



Benefits

- Reliably monitor the status of 2-wire Hall-effect sensors
  - Automotive grade solution works in harsh conditions
  - Withstands supply voltage transients up to 60V
  - Digital output filtering
- Provides flexibility
  - Easy interface to the microprocessor
  - Both analog and digital outputs are available
  - Wide supply voltage range operation

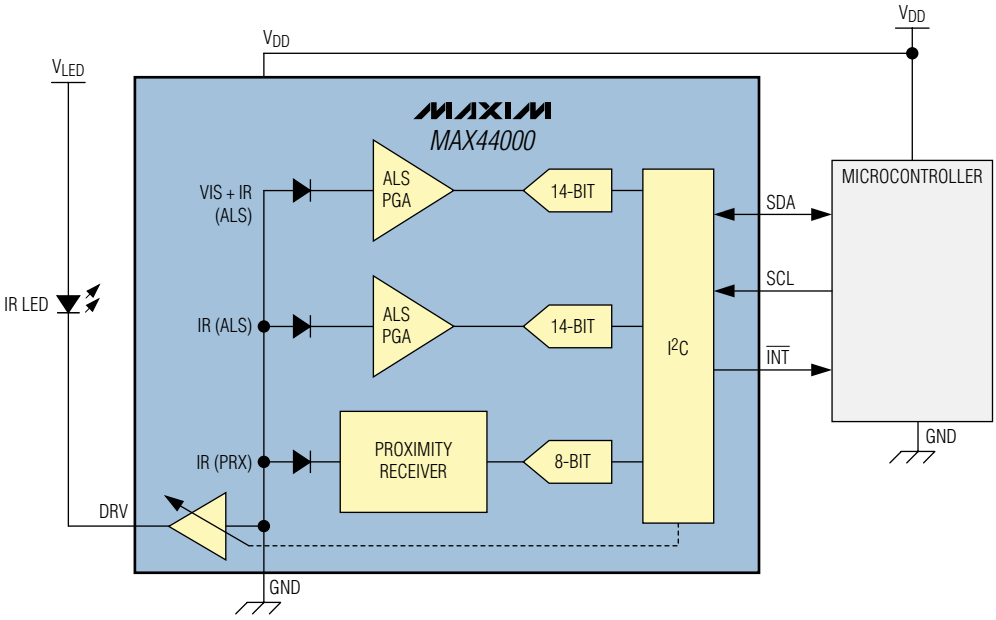
Integrated Digital Ambient Light and Proximity Sensor

MAX44000

The MAX44000 combines a wide dynamic range ambient light sensor with an integrated infrared proximity sensor.

While sensing both ambient light and proximity, the supply current, including the external IR LED current, can be as low as 11µA (time averaged).

The on-chip ambient light sensor operates over an extremely wide dynamic range (0.03 lux to 65,535 lux). To improve noise immunity, an on-chip IR proximity detector is matched with an integrated driver for the external IR LED. All readings are available on an I^2C communication bus. A programmable interrupt pin minimizes the need to poll the device for data, freeing up microcontroller resources, reducing system software overhead, and ultimately, reducing power consumption.



Benefits

- Minimizes power requirements
  - Ultra-low 1µA operating current consumption
  - V_{CC} is 1.7V to 3.6V, reducing the need for multiple supply rails
- Works in any lighting condition for valid measurements
  - Excellent IR and sunlight rejection for reliable proximity sensor operation
  - Superior light source matching for robust operation
- High integration simplifies system design
  - Sensors and ADCs are integrated in a tiny 2mm x 2mm x 0.6mm package
  - Built-in digital functions help to reduce time to market and reduce computation overhead for the microcontroller

Temperature and Humidity Data Logging

Overview

Data logging is a common requirement in control and automation systems as a way of providing confirmation of proper operation over time. The data logging function may be included as a part of a control system, or it may be a stand-alone function that can provide data independent of the main system. Temperature and humidity data loggers are particularly useful for a variety of purposes:

- Verification of operation of the system within specified temperature and humidity ranges. This may be done for troubleshooting or warranty purposes.
- Verification of proper storage temperatures of food and pharmaceutical products to assure safety and quality. This can be done in the factory or during transport.
- HVAC temperature/humidity tracking and troubleshooting
- Confirmation of proper temperature during chemical/pharmaceutical manufacturing

Temperature and humidity loggers employ the following blocks to measure and log temperature and humidity data:

- Sensors
  - Temperature sensors
  - Humidity sensors
- Timekeeping—generally in the form of a real-time clock (RTC)
- Nonvolatile memory, which can take many forms. Mechanical strip-chart recorders have been used for this purpose for many decades. Solid-state nonvolatile memory is common in recent designs.

These functions can be implemented at the board level or they can be integrated into a single solution. Some are designed for stationary installation, while others are small, battery-powered units that can be used for logging temperature and humidity during the transport of sensitive cargo such as food or medicine.

An example of an integrated, self-powered logger is Maxim's Hygrochron™ iButton® (DS1923), which includes an embedded humidity sensor and temperature sensor within an iButton package. The durable stainless steel iButton package provides protection against environmental hazards such as dirt, moisture, and mechanical impact. The tiny opening in the Hygrochron's lid uses a special filter that allows water vapor to pass through and reach the internal humidity sensor, but repels liquid-phase water (see **Figure 1**). Gathering both temperature and humidity data, the Hygrochron logs relative humidity as a function of time.

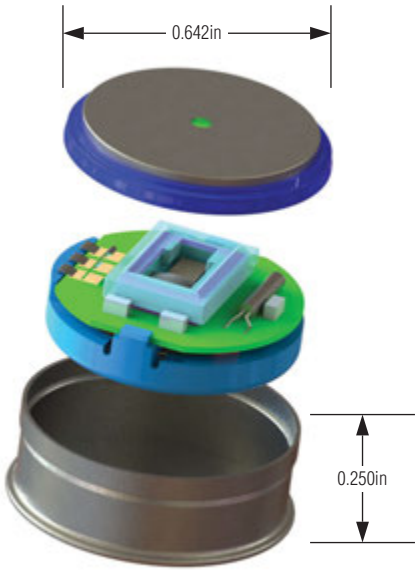
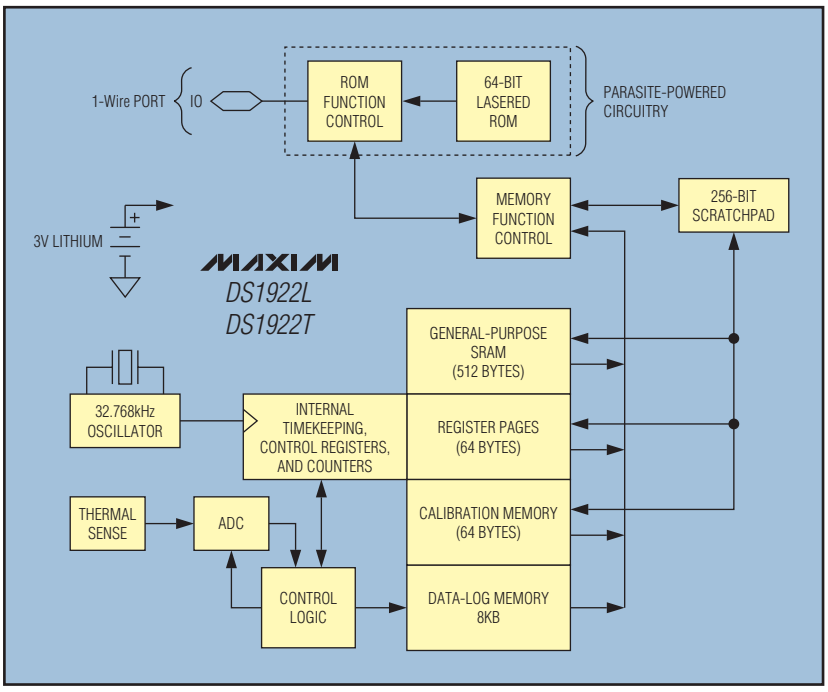


Figure 1. Illustration of the Hygrochron data logger shows the small size of the canister and how an outer filter allows water vapor to reach the device's internal humidity sensor.

High-Accuracy Digital Temperature and Data Loggers Offer Highest Data Integrity and Temperature Recording

DS1922L/DS1922T, DS1922E

The DS1922L/T/E iButton temperature loggers are rugged, self-sufficient systems that measure temperature and record the result in a protected memory section. The recording is done at a user-defined rate. A total of 8192 8-bit readings or 4096 16-bit readings taken at equidistant intervals ranging from 1s to 273hrs can be stored. Additionally, 512 bytes of SRAM store application-specific information and 64 bytes store calibration data. A mission to collect data can be programmed to begin immediately, after a user-defined delay, or after a temperature alarm. Access to the memory and control functions can be password protected. The DS1922 family is configured by and communicates with a host-computing device through the serial 1-Wire protocol, which requires only a single data lead and a ground return. The durable stainless steel package is highly resistant to environmental hazards such as dirt, moisture, and shock. The version with the highest operating temperature range (the DS1922E: +15°C to +140°C) can be used to monitor temperature in high-temperature logging applications such as pasteurization or steam sterilization.



Benefits

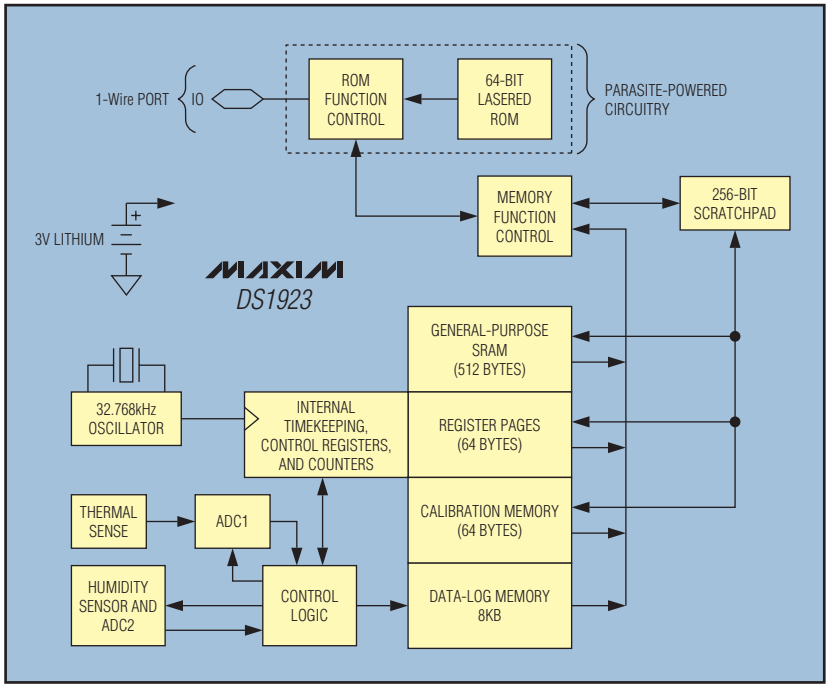
- Sophisticated, flexible temperature logging protects product integrity
  - Automatically wakes up, measures temperature and stores values in 8KB of data-log memory in 8- or 16-bit format
  - Sampling rate from 1s up to 273hrs
  - Programmable recording start delay after elapsed time or upon a temperature alarm trip point
- Precise, wide-range temperature measurement ensures accuracy
  - Digital thermometer measures temperature with 8-bit (0.5°C) or 11-bit (0.0625°C) resolution
  - ±0.5°C accuracy from -10°C to +65°C (DS1922L), ±0.5°C from +20°C to +75°C (DS1922T) with software correction
- Rugged and small container provides robustness and usage flexibility
  - Strong stainless steel enclosure
  - Complete solution in less than 0.1 cubic inch
- Safe, secure logging
  - Water resistant or waterproof if placed inside DS9107 iButton capsule (exceeds water resistant 3 ATM requirements)
  - Two-level password protection of all memory and configuration registers
  - Operating ranges: DS1922L: -40°C to +85°C; DS1922T: 0°C to +125°C; DS1922E: +15°C to 140°C
  - Meets UL 913, 5th Ed., Rev. 1997-02-24; intrinsically safe apparatus, approved under entity concept for use in Class I, Division 1, Group A, B, C, and D locations

Digital Temperature/Humidity Data Logger Ensures Accurate Reading

DS1923

The DS1923 temperature/humidity logger Hygrochron iButton is a rugged, self-sufficient system that measures temperature and/or humidity and records the result in a protected memory section. The recording is done at a user-defined rate. A total of 8192 8-bit readings or 4096 16-bit readings taken at equidistant intervals ranging from 1s to 273hr can be stored. Additionally, 512 bytes of SRAM store application-specific information and 64 bytes store calibration data. A mission to collect data can be programmed to begin immediately, after a user-defined delay, or after a temperature alarm. Access to the memory and control functions can be password protected. The DS1923 is configured and communicates with a host-computing device through the serial 1-Wire protocol, which requires only a single data lead and a ground return. Every DS1923 is factory lasered with a guaranteed unique 64-bit registration number that allows for absolute traceability. The durable stainless steel package is highly resistant to environmental hazards such as dirt, moisture, and shock.

Accessories permit the DS1923 to be mounted on almost any object, including containers, pallets, and bags.



Benefits

- Sophisticated, flexible temperature logging protects product integrity
  - Automatically wakes up and measures temperature and/or humidity
  - Stores temperature and humidity values in 8KB of data-log memory in 8-bit or 16-bit format
  - Sampling rate from 1s up to 273hr
  - Programmable recording start delay after elapsed time or upon a temperature alarm trip point
  - Programmable high and low trip points for temperature and humidity alarms
- Precise humidity and temperature measurement ensure accurate logging
  - 0.5°C or 0.0625°C temperature resolution
  - ±0.5°C temperature measurement accuracy from -10°C to +65°C with software correction
  - Built-in capacitive polymer humidity sensor for humidity logging
  - Hydrophobic filter protects sensor against dust, dirt, contaminants, and water droplets/condensation
  - Measures humidity with 5% accuracy, 8-bit (0.6% RH) or 12-bit (0.04% RH) resolution
- Rugged and small container provides robustness and usage flexibility
  - Strong stainless steel enclosure
  - Complete solution in less that 0.1 cubic inch
- Safe, secure logging
  - Two-level password protection of all memory and configuration registers
  - Operating Range: -20°C to +85°C
  - Meets UL 913, 5th Ed., Rev. 1997-02-24; intrinsically safe apparatus, approved under entity concept for use in Class I, Division 1, Group A, B, C, and D locations

Sensor Communications Interface

Analog Communication

A sensor communicates its "sensed" information with analog or digital techniques. Analog techniques are based on either voltage signals or current loops. The analog voltage signal range is typically from 0 to +10V, but can be as wide as -15V to +15V. Current loops are from 0 or 4–20mA. Analog signals go through an A/D converter (described in the *Analog Input Functions* section of the *Programmable Logic Controllers (PLCs)* chapter) and are digitized for the host controller to process.

Digital Communication

Binary

Binary sensors are digital sensors that only transmit single-bit information. The signal reads either as on/off, true/false, open/closed represented by a 1 and 0, and are typically unidirectional. The presence or absence of an object is detected and communicated with a logic level. For example, when an object like a piston in a valve reaches a predefined critical position, the sensor detects and communicates this to the PLC system through a binary interface. Industrial binary signals are often 0V and 24V. This high voltage swing provides good noise immunity.

Digital

The other type of unidirectional digital sensor can generate a range of digital values where each digital value represents a different measured level. For example, a digital flow meter sensor will output a higher digital value for fast flow and a lower one for a slower flow.

For bidirectional sensor communication, IO-Link is an emerging standard that enables a sensor to be more intelligent through configuring and monitoring over a standard 3-wire cable. Digital information is also communicated through CAN, RS-485, and other serial data interfaces.

Because industrial environments are harsh, sensor interfaces need to be robust to counter all forms of mishandling and EMI. Maxim offers a broad portfolio of industrial transceivers that integrates industry leading protection circuitry to handle fault, overvoltage, and ESD.

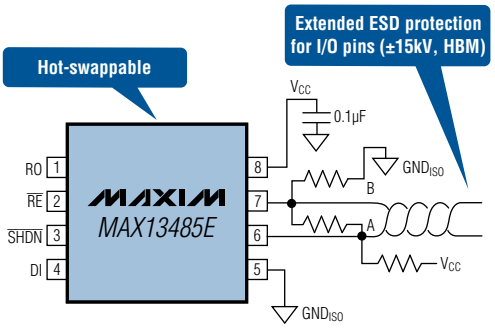
When selecting a sensor communications interface, consider the following:

- Distance analog signal must travel to digitizer
- Drive capabilities of analog or digital sensors
- Distance digitized signal must travel
- Unidirectional or bidirectional data and control flow
- Whether half-duplex or full-duplex data is required
- Data rates required
- Response time required between sensor signal and system controller
- ESD, EMI/RFI, overvoltage, and other fault protection and fault response
- Power consumption
- Solution size
- Ease of installation
- Network topology

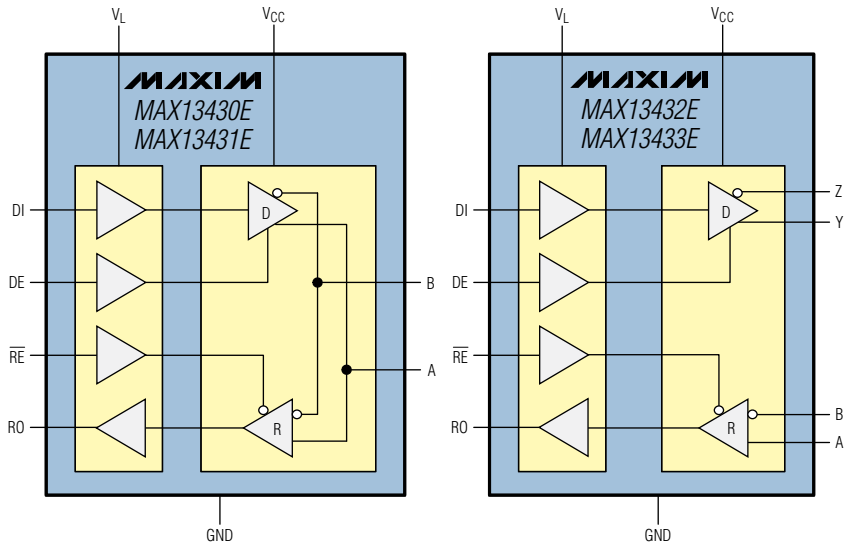
Industry's Smallest RS-485 Transceivers Save Board Space and Reduce BOM Complexity

MAX13485E/MAX13486E, MAX13430E–MAX13433E

As industrial modules become smaller, pressure mounts for PLC designers to shrink their PCBs and transition from the traditional industry-standard packages like SO, SSOP, and PDIP. Maxim offers a full family of RS-485 transceivers available in tiny µDFN/TDFN packages with integrated features that reduce BOM complexity, board space, and cost.



Packaged in a µDFN, the MAX13485E saves more than 50% board space compared to the competition.



Typical operating circuits of the MAX13430E product family.

Benefits

MAX13485E/MAX13486E

- Smallest footprint enables compact designs
  - Space-saving, tiny 8-pin µDFN (2mm x 2mm) package
- High integration reduces BOM complexity
  - Hot-swap operation eliminates false transitions during power-up/live insertion
  - Enhanced slew-rate limiting facilitates error-free data transmission
  - Low-power shutdown modes reduce power consumption during idle operation

MAX13430E–MAX13433E

- Smallest footprint enables compact designs
  - Available in tiny 10-pin TDFN/µMAX (3mm x 3mm) packages
- Flexible configurations for interfacing to many applications, thus reducing inventory
  - Wide 3V to 5V supply reduces need for 5V supply
  - Integrated V_L pin allows interface with low-voltage logic (down to 1.62V logic) FPGAs and ASICs
  - Enhanced slew-rate limiting facilitates error-free data transmission
  - High ±30kV (HBM) ESD protection provides the industry's most robust protection

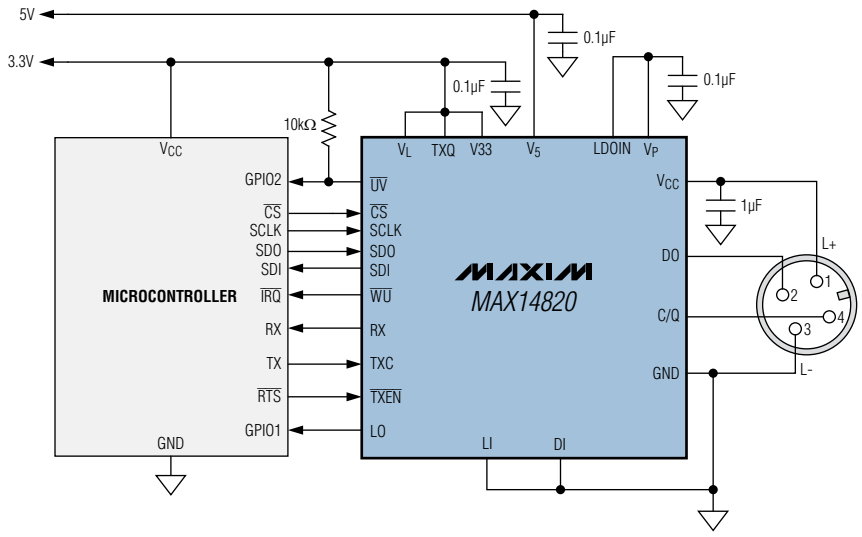
Reduce PCB Footprint with IO-Link/Binary Sensor Interface

MAX14820, MAX14821

The MAX14820 and MAX14821 are transceivers with a 24V binary interface for sensors and actuators. Designed for IO-Link device applications, they support all the specified IO-Link data rates. The MAX14820 has a minimum C/Q drive of 300mA, while the MAX14821 has a minimum drive of 100mA. Both of these devices contain additional 24V digital inputs and outputs (I/Os). The auxiliary digital output for the MAX14820 is rated for 135mA minimum current drive, and the MAX14821's auxiliary digital output is rated for 100mA. Designers have the option of utilizing the reverse polarity protected 24V V_P line for external regulation, or the two built-in 5V and 3.3V linear regulators for common sensor signal and conditioning power requirements. The drivers are configurable to pnp, npn, and push-pull. Configuration, monitoring, and alarms are accessed through an SPI interface. The devices are thermally self-protected and all 24V interface pins are protected against reverse-polarity, shorts, and ESD. Both the MAX14820 and MAX14821 are packaged in a 4mm x 4mm TQFN, while the MAX14821 is also offered in a 2.5mm x 2.5mm WLP. All packages are rated for -40°C to +85°C industrial operating temperature range.

Benefits

- Internal or external power regulation provides flexibility in design
  - Reverse polarity-protected 24V V_P line for powering external regulator
  - Two built-in regulators of 3.3V and 5V for lower power requirements
- High integration of feature set to maximize performance and minimize board space
  - Wake-up detection alleviates processing load for microcontroller
  - High C/Q drive capability for up to 1µF capacitive loads
  - Dual digital outputs and inputs fit most sensor needs
  - SPI interface for configuration and monitoring
  - Tiny 2.5mm x 2.5mm WLP (MAX14821)
  - Requires minimal external components



The MAX14820 IO-Link/binary-sensor interface reduces PCB footprint.

Recommended Solutions

Pressure Sensors and Weigh Scales

Part	Description	Features	Benefits
ADCs			
MAX1415/16 MX7705	16-bit, low-power, 2-channel, sigma-delta ADCs	Two differential channels, PGA, single-supply operation	Highly flexible ADC; interfaces with a wide range of sensors.
MAX1400/01/02/03	18-bit, 5-channel delta-sigma ADCs	Three differential channels, PGA, precision current sources for excitation, burnout detection	High integration produces a more precise sensor that measures both pressure and temperature with one ADC.
MAX11040K	24-bit, 4-channel, simultaneous sampling sigma-delta ADC	Cascadable up to 32 channels, 106dB SNR at 16ksps, overvoltage protection (OVP)	Eases interface design for sensors that require accurate multichannel amplitude and phase data.
MAX11200/01/02	Ultra-low-power, sigma-delta ADCs	21-bit noise-free range at 10sps, 3V supply, 0.45mW, four GPIOs	Enable very high-resolution sensor interfaces with minimal impact on power budget.
Signal Conditioners			
MAX1454	Precision sensor signal conditioner with over/reverse voltage protection	45V over/reverse voltage protection; input fault detection, 16-bit resolution with 6V/V to 2048V/V signal path gain	Protects against power transient/ surge and enhances safety.
MAX1452	Low-cost, precision sensor signal conditioner	Multitemperature calibration, current and voltage excitation, fast 150µs response, single-pin programmable, 4–20mA applications	Integrated signal-conditioner simplifies designs and fits a wide range of sensor applications.
MAX1464	Low-power, low-noise, multichannel, digital sensor conditioner	Integrated 16-bit ADC, DACs, and CPU; programmable compensation algorithm; digital, analog, and PWM outputs; 4–20mA application	Accurate signal conditioner interfaces directly with microcontroller to save space.
Amplifiers			
MAX9617/18	Ultra-precision, zero-drift op amps	1.5MHz gain bandwidth (GBW), 59µA supply current, 10µV (max) zero-drift input offset voltage (V_{OS}), single and dual packaging versions	Provide high-precision measurements for a wide variety of low-frequency applications.
MAX9943/44	High-voltage, precision, low-power op amps	Wide 6V to 38V supply range, 2.4 MHz GBW	Provide design flexibility for a wide range of applications.

For a list of Maxim's recommended pressure-sensor solutions, please go to: www.maxim-ic.com/psi.

Temperature Sensors

Part	Description	Features	Benefits
Thermal Management			
DS600	Precision analog-output temperature sensor	Industry's highest accuracy analog temp sensor: ±0.5°C from -20°C to +100°C	Improves thermocouple interface designs with industry's best analog cold-junction accuracy.
DS7505	Low-voltage, precision, digital thermometer and thermostat	±0.5°C accuracy from 0°C to +70°C, 1.7V to 3.7V operation, industry-standard pinout	Industry-standard pinout allows easy accuracy upgrade and supply-voltage reduction from LM75.
DS18B20	Precision 1-Wire digital temperature sensor	±0.5°C accuracy from -10°C to +85°C, 1-Wire interface, 64-bit factory-lasered ID code	Enables simple networking of precision temperature sensors with minimal wiring.
MAX31855	Thermocouple-to-digital converter	Built-in cold-junction compensation; versions available for Type J-, K-, N-, R-, S-, T-, and E-thermocouples	Simplest thermocouple interface; no external components needed.
Data Logging			
DS1923	iButton temperature and humidity data logger	Automatic humidity logging at ±5% accuracy and temperature logging at ±0.5°C accuracy at rates from 1s to 273 hrs in small rugged package	Compact, complete humidity and temperature data logger for rugged environments.
DS1922L/T/E	iButton temperature data logger	Automatic temperature logging at ±0.5°C accuracy at rates from 1s to 273 hrs in small rugged package	Compact, complete temperature data logger for rugged environments.
ADCs			
MAX1300*/01/02*/03	16-bit, 8-/4-channel SAR ADCs with software-programmable input ranges	Input range from ±12V to 0 to 2.048V, ±16.5V overvoltage-protected inputs, PGA, internal reference	Reduce design complexity when working with sensors with multiple output ranges.
MAX1415/16 MX7705	16-bit, low-power, 2-channel, sigma-delta ADCs	Two differential channels, PGA, single supply	Provide flexibility to interface with a wide range of sensors.
MAX1400/01/02/03	18-bit, 5-channel, sigma-delta ADCs	Three differential channels, precision current sources for excitation, burnout detection	A single ADC simplifies temperature-sensor design for accurate thermocouple and RTD measurement.
MAX11200/01/02	Ultra-low-power, sigma-delta ADCs	21-bit noise-free range at 10sps, 3V supply, 0.45mW, 4 GPIOs	21 bits of noise-free range with minimal impact on power budget.
Amplifiers			
MAX9617/18	Ultra-low-power, zero-drift op amps	1.5MHz GBW, 59µA supply current, 10µV (max) zero-drift input offset voltage (V_{OS}), single and dual packaging versions	Provide high-precision measurements in a wide variety of low-frequency applications.
MAX9943/44	High-voltage, precision, low-power op amps	Wide 6V to 38V supply range, 2.4MHz GBW	Design flexibility for a wide range of applications.
MAX9939	SPI PGA with on-demand calibration and differential in/out configuration	Input supports negative voltages, wide range of gain configurations, input-error nulling feature	Calibration on-demand improves system accuracy; minimizes harsh environmental noise.

For a list of Maxim's recommended temperature-sensor solutions, please go to: www.maxim-ic.com/-40+85.

*Future product—contact the factory for availability.

Light Sensors

Part	Description	Features	Benefits
Ambient Light Sensors			
MAX44009	Digital ambient light sensor	1µA ultra-low power and 22-bit wide dynamic range operation with automatic gain control	Precision light sensing in a small space.
MAX44007	Digital ambient light sensor with IR sensor	1µA ultra-low power and 22-bit wide dynamic range operation with automatic gain control down to 0.025lx sensitivity	Precise ambient light and IR sensing with board space and cost saving.
MAX44004*	Digital ambient light sensor	5µA low power with IR sensing and 0.03lx sensitivity, -40°C to +105°C operating range, 1.5ms conversion time	Meets stringent speed requirements; wide temperature range allows operation in harsh environments.
RGB-IR Color Sensors			
MAX44006*	RGB-IR-ambient-temperature sensor integrated with proximity sensor	1.8V multiband ultra-sensitive digital light sensor with digital functions and wide temperature range	Reduces component count and provides reliable optical measurements.
MAX44008*	RGB-IR-ambient-temperature sensor integrated with proximity sensor	2.7V to 5.5V wide supply range multiband ultra-sensitive digital light sensor with digital functions and wide temperature range	Reduces component count and provides reliable optical measurements.
ADCs			
MAX1167/68 MAX1162	16-bit, 200ksps, 8-/4-/1-channel SAR ADCs	16-bit, no missing codes; single 5V supply; unipolar 0 to 5V input range	Flexible and accurate solution for multichannel applications.
MAX11200/01/02	Ultra-low-power, sigma-delta ADCs	21-bit noise-free range at 10sps, 3V supply, 0.45mW, 4 GPIOs	Use lower power while enabling accurate measurements over a 20klx to 100klx range.
Amplifiers			
MAX9945	Low-noise, MOS-input, low-power op amp	4.75V to 38V supply voltage range, low input-bias current, low input-current noise	Low input-bias current (fA) maximizes system accuracy.
MAX4230–MAX4234	High-output-drive, rail-to-rail I/O op amp series	200mA output-drive capability, 10MHz GBW, 10µV/s high slew rate	High drive current extends communication distance.
MAX4475–MAX4478	Low-distortion, CMOS-input op amp series	0.0002% THD+N, low input-bias current, 10MHz GBW	Provide more accurate ADC input signal.

*Future product—contact the factory for availability.

Proximity Sensors

Part	Description	Features	Benefits
Proximity Sensors			
MAX44000	Integrated proximity sensor and ambient light sensor	7µA low-power IR-based reliable proximity sensor integrated with 0.03lx sensitive ambient light sensor	Single IC provides proximity and light sensing with wide dynamic range and digital functions for reliable sensing in harsh environments.
MAX44005*	RGB-IR-ambient-temperature sensor integrated with proximity sensor	12µA low-power multiband light sensor with temperature compensation and high sensitive proximity sensor	High-performance proximity sensor integrated with multiband light sensor for fast and reliable color digitization.
MAX9621	Dual, 2-wire Hall-effect sensor interface with analog and digital outputs	Wide supply range with supply transient detection; filtered digital and analog outputs for wide range of interfaces	Provides flexibility and cost saving for Hall-effect sensor applications.

Sensor Communications Interface

Part	Description	Features	Benefits
Interface Transceivers			
MAX14820	300mA IO-Link device transceiver	High C/Q driver capability up to 1µF, protected V_P, wake-up detection	Allows heavy capacitive loads.
MAX14821	100mA IO-Link device transceiver	Tiny 2.5mm x 2.5mm WLP form factor, protected V_P, wake-up detection	Reduces board area; offers flexible power options; simplifies firmware development.
MAX14824	IO-Link master transceiver with 300mA drive	IO-Link v.1.0, v.1.1 compliant; COM1, COM2, COM3 data rates	Feature integration saves space.
MAX14830	IO-Link UART	IO-Link 1.1 compliant quad-channel, 128-word FIFO	Extends functionality of microcontroller.
MAX13485E/86E	Half-duplex RS-485/422 transceivers in µDFN	8-pin, 2mm x 2mm, µDFN package; hot-swap capable, ±15kV ESD protection	Smallest package and internal protection circuitry yield extreme board space savings and ruggedness.
MAX13430E/1E/2E/3E	RS-485 family with low-voltage logic interface in TDFN-EP and µMAX packages	10-/14-pin, 3mm x 3mm, TDFN-EP and µMAX; low-voltage logic interface down to +1.62V, ±30kV ESD HBM	Tiny package, integrated logic level translator and ESD circuitry yield smallest board footprint solution.

*Future product—contact the factory for availability.

Environmental Automation

Introduction

Environmental automation refers to the automated controls for systems that regulate the environmental conditions of the interiors of all kinds of buildings. Systems for commercial buildings—office buildings, skyscrapers, hospitals, etc.—are called building automation systems (BASs) or building management systems (BMSs). Systems for residential buildings—homes and apartments—are called home automation systems (HASs). There are similarities between BASs and HASs, but there are also significant differences. BASs are often much more complex and often control systems do not exist at all in HASs. HASs control some items that are not found in BASs, but there is overlap.

In this section, we survey the equipment found in buildings and briefly discuss their operation, sensors needed, and the signaling and control aspects of automating their operation. There is significant overlap with content provided elsewhere in this guide, so where appropriate the reader will be referred to other sections or chapters.

At first one might think that the environment for this equipment is not as harsh and its operation not as critical as that in a factory process-control environment, but one need only realize that this equipment is just as likely to be installed in a hospital as in a shopping mall. With patients' lives dependent on proper room conditions, power, and water supply for their life-sustaining needs, these systems must be very reliable. Furthermore, in large buildings, these systems are likewise large and require large amounts of energy to run. For example, large air conditioning systems can draw huge amounts of power, much more than in some smaller factories, so large switching load transients are common. Air conditioning systems can build up static electricity due to low humidity airflows, so ESD strikes are not uncommon. One can see that robustness, reliability, protection from fault conditions, surge handling capability, and ESD protection are just as important in equipment used for environmental automation as they are in factory automation.

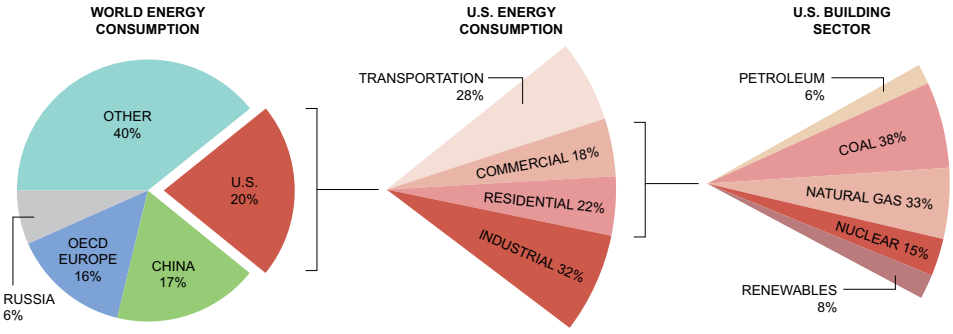
According to The Office of Energy Efficiency and Renewable Energy (EERE), in its *Buildings Energy Data Book*, between 2002 and 2008 40% of U.S. primary energy was consumed in the buildings sector. The industrial sector was responsible for 32% and the transportation sector 28% of the total. Of the 40% consumed in the buildings sector, homes accounted for 54% and commercial buildings accounted for 46%. As for energy sources, 76% came from fossil fuels, 15% from nuclear generation, and 8% from renewable. Efficiency improvements and usage reductions in primary energy consumption can lead to substantial savings.

Home Automation Systems (HASs)

The low-cost personal computer, Internet, and a variety of radio technologies available to transfer digital data at high speeds have enabled a market for home computerized appliances and home control systems. Monitoring and control can now be done automatically and remotely to enhance security, convenience, comfort, ambience, and energy conservation of the modern household.

With a home-based local area network using Ethernet and open-source embedded operating systems like Linux®, the following systems can all be tied into the HAS: heating, ventilation, air conditioning (HVAC), major appliances, security systems, lighting, home entertainment systems, irrigation systems, and even pet feeding and domestic robots. Low-cost WAN technology like digital cable and DSL, initially provided to deliver entertainment, can now be used to provide monitoring, remote control, and automation of home environments for security, energy savings, and convenience.

While the optimum time to install an HAS is during new construction when the walls are exposed, it is becoming easier to retrofit existing homes with automation systems using wireless technologies. One example bridges cabled Ethernet to Wi-Fi® and transmits data through powerline communications such as HomePlug® devices.



Estimated U.S. energy use between 2002 and 2008 (Source: Buildings Energy Data Book from The Office of Energy Efficiency and Renewable Energy (EERE)).

Building Automation Systems (BASs)

Technical floor of a smart building HVAC system.

A building is much like a factory in that it is expected to be efficient, and, as in factories, a more efficient building is both more productive and less costly to operate.

Aside from electric lighting, the most dramatic example of automation affecting the design of a building is the humble elevator. In fact, without the elevator, today's modern cities would have a distinctively different look. The elevator has made it practical to stack story upon story, enabling modern skyscrapers. While we take the operation and availability of the elevator for granted today, and while it is a relatively simple device (it really only goes up and down), the elevator has been made increasingly productive over time through the development of complex control algorithms that maximize the ability of an elevator to both fill and empty a large building in a short time.

As time progresses, and as the relative costs for labor, materials, and energy have changed, buildings too have changed to be more economical. Today, for example, buildings can be economically constructed with relatively low-cost materials like steel, concrete, and glass. This combination allows the construction of large towers that are strong and stable, even in earthquake-prone areas. But to make these buildings economical for use, attention must be paid to ongoing expenses like energy and water usage, especially when the cost of energy is outpacing inflation and new renewable energy resources become available. To continue to meet occupants' expectations of comfortable and productive work environments, optimizing energy usage, which leads to savings, is essential. This optimization requires more sophisticated environmental controls and monitoring systems.

In the past, building automation centered on efficiently moving people, freight, and other items like mail. Today building automation focuses on energy management and communications. Because energy management and communications are based on sensors and computer control, the use of semiconductor technology within buildings for the purpose of reducing and controlling costs has rapidly escalated. For technology providers today, building automation is a large, growing, and relatively untapped market.

BASs have evolved along with factory automation systems to now use distributed processing elements networked together; they are truly distributed control systems (DCSs).

BASs provide similar advantages as DCSs in factory automation systems such as reduced cabling, faster response to sensor inputs, improved data gathering, comprehensive communications resulting in enhanced operations, and easier upgrades and modifications.

These systems enable building energy measurement and management, water supply monitoring and processing, HVAC and refrigeration (HVAC&R), lighting systems, security and access control systems, occupancy response systems, elevators, escalators, moving walkways, and fire safety systems. In hotels, the hospitality systems (room reservations), Internet access, food services, and conference room automation systems are based on similarly constructed distributed processing systems linked by communications channels that either flow via firewalled LANs or wireless connections. BASs connections to system controllers use few wireless links and mostly rely on physical cabling, sometimes including powerline communications. This is due to the long distances involved, the high data loads, and the high criticality of the data communications.

The primary differences between a factory automation system and a BAS are in the types of equipment, network protocols, and terminologies used. Control systems are very similar to PLCs. Often standard industrial PLCs are used in BASs. Because the networks used must be robust, as in factories, and the human machine interfaces must provide timely and comprehensive information, many of Maxim's products suited for the factory environment are also suited for BASs. Usually in BASs data rates can be slower and the environments are often not as harsh as in high-speed production factories. But, as mentioned in the introduction, a BAS and its related equipment can be critical to occupants' safety and well-being, so robust equipment design and dependable fail-safe operation is required.

Water Supply Systems

Because water is needed in any residential or commercial building, water supply systems are critical to the design. It is often assumed that a building will have a reliable, clean supply of water, but the water supply from a city system may not meet the water purity standards of some establishments or even for some home use. "Domestic" water for hotels and other commercial establishments is sometimes supplied for use only after being treated in a variety of ways, which include filtering, softening, and disinfection.

Water Pressure

Very tall buildings create a water pressure problem. In a static column of water, the pressure drops 1 decibar for every meter of height or 4.33lb/sq in for every 10ft. In multiple-story buildings, floors are separated by approximately 10ft, so in a 100-story skyscraper the pressure drop is 43psi. This is enough of a drop so that fixtures do not operate properly. To remedy this, pumps are needed to create pressure for the upper floors, and pressure-reducing valves are needed to keep pressures within acceptable ranges for the fixtures. Noninstrumented systems may seem adequate when everything is working properly, but when leaks occur or pipes break, water damage can quickly mount. Pressure sensors (see the *Pressure Sensors and Weigh Scales (Force Sensing)* section in the *Sensors* chapter) and electronically controlled shutoff valves strategically located throughout the system can quickly isolate a region around the failure and alert the BAS of the problem and its location. With proper plumbing design, large areas of the building remain unaffected while repairs are made. By implementing pumps driven by motors with variable-speed drives (see the *Motor Control* chapter), pressure surges are limited, thereby reducing "water hammer" and the strain it places on the plumbing. Power consumption is also reduced to match the amount that is adequate for the usage rate.

Tall buildings always have several floors below ground level, so pumps are needed to push waste water back up to surface drainage levels. Sump pumps, water level detection, filtration, and additional treatment equipment can be used with monitoring and control systems tied into the BAS.

Water Filters and Softeners

In developed countries, "city" water is generally good enough for washing and most other uses, but the use of home filtration systems ensure that water is contaminant-free and actually tastes good. Soft water reduces scale buildup and extends the effectiveness of soaps and detergents. Home filters and softeners are usually not (yet) connected to an HAS; they just incorporate local controls and indicators, but eventually incorporating these types of devices will provide the benefit of automated notifications for malfunctions and the need for maintenance.

In commercial buildings, incoming water also may not meet standards of cleanliness the facility needs, so filters and softening systems are often employed. But filters need to be changed periodically, and softening systems need a salt supply and other periodic maintenance. If a filter system has no sensor, relying on the calendar to predict when to change the filter may be inadequate because both water-usage rates and sediment levels can vary over time and season. By monitoring the flow rates and measuring the total volume flowing through the filter, a better estimate is achieved. But if sediment levels are unpredictable, this tracking method can also fall short of indicating the best time to change the filter. The best method is to monitor the pressure drop across the filter element when the flow rate is at some nominal level. Pressure vs. flow-rate charts can be generated for new vs. clogged filters. Pressure sensors on both sides of the filter and a flow-rate sensor are needed. Additionally, a temperature sensor is needed since the water temperature usually affects the readings of pressure sensors (see the *Sensors* chapter). Data from these sensors can then be gathered, communicated to a monitoring system, and processed. The result indicates when it is time to change the filter (see the *Programmable Logic Controllers (PLCs)* chapter). Additionally, detection of pressures that are too low across the filter may also be needed if a filter blowout failure is possible. With instrumentation to detect pressure, maintenance levels are reduced, filter life is maximized, water pressure drop is kept within reasonable levels, and failures are detected immediately, assuring high water quality.

For softeners, similar pressure and temperature sensing is needed on large systems including saline concentration, salt supply, and potentially other parameters. There are various types of softeners, so other chemical-sensing systems are possible. Automatic salt-feeding systems can be incorporated when regeneration is needed and their proper operation may need to be monitored.

Water Heaters and Boilers

In residential buildings, water heaters are usually small and simple since they supply individual residences with domestic hot water (DHW), and they are typically not (yet) tied into any HAS. But in larger residential buildings and commercial buildings, the water heating systems are large capacity and instrumented. Water heaters are quite straightforward. Inlet and outlet temperatures as well as flow rate can be monitored and used to predict the heating rate needed, as opposed to simply watching the output temperature and responding when it changes. This improved instrumentation and the use of the computational power of the BAS results in more consistent output temperatures under varying inlet water temperatures, ambient temperatures, and flow rates. This instrumentation provides energy savings. If the controller is given predictions of

usage needs, such as known low DHW usage in a building during the night, it can allow the temperature to drop, which could save energy.

Boilers create steam that is often used by the HVAC system. Some "combi" boilers not only create steam, but also DHW. There are many types of boilers and steam generators with a variety of instrumentation and control needs.

In the past, boiler explosions were quite common because there were no sensors or indicators to warn of dangerous conditions. Boilers that are allowed to run dry become extremely dangerous as they overheat quickly. If any water is introduced while the boiler is still hot, the water instantly flashes to steam and its rapid expansion can cause a violent explosion. One of the purposes of implementing sensors is to reduce the risk of these failures. Today boiler explosions are rare due to the use of sensors and automated controls provided by a BAS. Boilers can be monitored completely and continuously, and problems responded to automatically. Some boiler types operate at very high pressures and temperatures. There are "superheated steam boilers" and "supercritical steam generators" operating in the 1500°C range and at pressures in the 3000psi range. A boiler is specified by stating the steam production rate. In the U.S., the metrics for a boiler's output might be 1000lb/hr at 100lb/sq in and 500°F. Multiple-story tall boilers in industrial plants can produce as much as 300,000lb/hr at 350psi and 600°F. The steam generated from these is most commonly used to power turbines that run alternators to generate electricity.

Boilers need water level sensors, pH sensors, temperature sensors (like the MAX6603 platinum RTD-to-digital converter), pressure sensors (see the *Pressure Sensors and Weigh Scales (Force Sensing)* section in the *Sensors* chapter), steam flow-rate sensors, water flow-rate sensors, and valve position sensors (like the MAX9621 Hall-effect sensor interface and the MAX9924 VR sensor). There are numerous types of valves used (low-water cutoff valve, overpressure safety valve, blowdown valve, check valves), circulating pumps, pressure regulators, chemical injection systems, fuel-feed systems, and firebox controls. Signals from the sensors and controls to these components are handled by PLCs or similar controllers built into the boiler (see the *Programmable Logic Controllers (PLCs)* chapter). Operating data and system level controls are communicated to and from the BAS.

Boiler room in a commercial facility.

Heat Exchangers

In some locations, "district heating" is used. In these cases, "waste" heat from industrial installations produces enough heat for the heating of water and space in local neighborhoods. Heat exchangers transfer the heat from the supply system to potable water systems in the residence, thereby preventing the two water supplies from mixing.

To maximize efficiency of heat transfer across the boundary, heat exchangers often contain many small tubes carrying one fluid while being immersed in another fluid. These can foul over time. Partial clogging can cause significant pressure drop across the inlet to outlet ports on either side of the heat exchanger. Pressure-drop sensing is needed in commercial and larger residential applications. Pumps can be employed to overcome the inherent flow restriction in heat exchangers, and variable-speed drives for these pumps can be used to provide more control over the speed of the flow to optimize the heat transfer and the energy used by the pump motor (see the *Motor Control* chapter).

HVAC&R Systems

Introduction

HVAC&R equipment performs space heating and/or cooling and refrigeration for residential, commercial, and industrial buildings. The HVAC&R system is responsible for providing fresh outdoor air to ensure that CO_2 levels do not get too high for the occupants; to heat, cool, and control humidity levels; and to dilute or remove airborne contaminants such as volatile chemicals, cooking smoke, and other airborne particles. A properly designed and maintained system provides a comfortable indoor environment year-round under a wide range of usage conditions. The HVAC&R system is also known as climate control, which can be quite involved.

Occupancy Response

An occupancy response system enhances the operation of the HVAC and lighting systems, providing greater convenience, comfort, and energy savings. These systems predict occupancy based on day of the week, time of day, and special events programming. They pre-warm or pre-cool living spaces in anticipation of the need for room temperatures to be comfortable prior to the occupant's arrival. Due to thermal lag, the heating or cooling of these spaces must start many minutes to many hours in advance. In large buildings with crowds of people entering the building to start their work day or to attend a large event, anticipating this thermal load on the system is critical. Additionally, depending on the season and on the weather, skyscrapers in the morning receive significantly different solar-heating effects on the east side of the building than on the west side, with the opposite effect in the afternoon. This problem can be solved by either expending energy or by properly designing a system to respond to the presence of an occupant, which would result in energy savings. System-inlet air-temperature sensing, the solar load data, and weather reports, along with the other factors mentioned, all play a role in system's ability to conserve energy while providing the optimum environment for the occupants.

HVAC Equipment

It is not always possible to separate components of HVAC&R systems into heating, ventilation, AC, and refrigeration systems because many components are used for multiple purposes. Instead, we will discuss commonly used equipment for HVAC&R systems and describe the equipment's basic functions and controls.

Furnace

If "district heating" is not available, then homes with central heating have a furnace with air ducts to carry the warm air to individual rooms. Commercial buildings may use furnaces if boilers and steam systems are not used. A furnace must have a fail-safe control loop between the burner and fan. Whenever the temperature is above a set point, the fan must turn on to prevent the burner from overheating. The fan remains on until the temperature has dropped to the set point. A significant amount of hysteresis is programmed into the system to ensure that all the heat is pushed through the ductwork to the rooms. A temperature sensor is needed in the furnace plenum to control this action. For this control, a thermistor or platinum RTD-based probe is usually used. Maxim's MAX6603 RTD-to-voltage signal conditioner provides a dual solution for redundancy that can enhance fail-safe designs. A thermocouple is common for high temperatures inside the furnace; Maxim's MAX31855 thermocouple-to-digital converter is a good solution. If an error or overtemperature is detected, the burner shuts off and an error flag is set. An error is also indicated if the burner fails to ignite for some reason. Gas must be shut off immediately. These controls are always built into the furnace. The BAS will simply be told that these problems have occurred.

Home air conditioner.

Chiller

A chiller drops the temperature of water through the use of the vapor compression or the absorption refrigeration cycle (see the *Refrigeration* section in this chapter for a brief explanation). The cold water is pumped throughout the building to air handling units (AHUs) to provide the air cooling needed. Chilled water systems bring the water down to 1.5°C to 7°C depending on the requirements of the system. (Chillers are not only used in HVAC systems. They are used in a wide variety of processing plants to speed the cooling of many products that are hot from molding, cutting, casting, etc.). Vapor compression chillers now use variable-frequency drives (VFDs) on their motors to increase efficiency (see the *Motor Control* chapter). Sensing includes temperature at the inlet and outlet, water pressures (see the *Pressure Sensors and Weigh Scales (Force Sensing)* section in the *Sensors* chapter), flow rates, and similar parameters for the refrigerant fluids. Heat exchangers are used on the evaporator and condenser to maximize heat transfer from the refrigerant to two separate water

systems. On the evaporator, the heat exchanger transfers the coldness into the water to be piped throughout the building for cooling in the AHUs and related equipment. On the condenser, the heat exchanger warms water that is carried away, often to cooling towers on the outside of the building that are designed to discard this heat. After being cooled by the tower, this water returns to the condenser heat exchanger, coming full circle. More efficient installations may use this "waste" heat for pre-warming water that is ultimately used for steam heat or DHW use.

The need for many types of sensors and controls is evident on a chiller system. The usual sensors such as temperature, pressure, and flow rate are needed in several areas. Controls are needed for valves and for motor speed. There are several opportunities for energy savings. Savings can result through flexible responses to varying loads on the system, which are influenced by outside temperatures and occupancy usage rates. For example, under a light usage load, instead of pumping water at full capacity through the system, the rate of water flow can be reduced.

Chiller room for a building cold water system.

Control Panels

On all the systems discussed so far and on those to be discussed, there is always some kind of control panel with input devices and indicators, even if the equipment will be completely controlled by its network interface to an HAS or BAS. There will be at least emergency stop buttons, usually manual start/stop buttons, and potentially several other controls from simple pushbuttons and dials to touch screens on the complex machines. Indicators can range from only a few LEDs to full graphic displays on complex machines. Touch screens, which use graphic displays, are becoming common.

For most industrial applications, resistive touch-screen controllers like the MAX11800 are simple to implement, and they prevent responses to multiple simultaneous touches. For pushbutton interfaces, the MAX16054, a ±15kV ESD-protected switch debouncer, makes it easy to avoid any failures or false inputs at this interface. LEDs, due to their robustness and long life, have completely replaced incandescent bulb indicators. To drive several LEDs for indicators or backlighting, the MAX6979 offers LED fault detection and watchdog features to provide assurance that LED indicators are working properly.

Control panel with a variety of input and output types.

Thermostat

Programmable electronic thermostats in homes and similar, but more sophisticated systems for commercial buildings keep track of time and days of the week, allowing for temperature profiles that increase comfort and save energy. In a home, for example, a programmable thermostat performs slow, energy-efficient heating in the morning in anticipation of occupants getting up to start their day. A slow-heating cycle is accomplished by the thermostat slowly ramping up the set-temperature point over a period of an hour, so the heater does not constantly run due to a large step function setting change. Similarly, a temperature drop during the middle of the day, when the home will be unoccupied, can be programmed, followed by a second warming in the evening for the occupant's return. On weekends, the morning cycle can be delayed and the mid-day temperature dip can be removed. In commercial buildings, individual rooms can be programmed with similar anticipatory temperature profiles.

Most home thermostats use custom ASICs for the bulk of their functions—real-time clock, temperature sensing, µP, communication. But if individual components such as these are needed outside of the ASIC for safety, redundancy, or accuracy, use the DS7505 thermostat, the MAX6682 thermistor-to-digital converter, or the MAX1472 ASK transmitter for wireless communication from the thermostat to the furnace.

Wireless communication between the thermostat and the HVAC system is common in homes and some businesses, but the limited range of most of these systems curtails their use in large facilities. For more details, see the *Wireless Systems* section in this chapter.

Damper

Dampers are air valves similar in concept to those found in fireplace chimneys. They can be controlled by simple mechanical levers, relying on a person to operate, or they can be controlled by electric motors, vacuum actuators, or compressed air actuators. They direct air into different paths in response to commands from the HVAC controller portion of the BAS. The dampers can respond as needed to achieve individual room temperature profiles that had been programmed into the system. This complex system, to be fully effective, needs room temperature sensing, thermostat communication with the heating system, and a damper actuator drive with position sensing. This position sensing is fed back into the BAS to confirm that the damper responded correctly.

Rooftop unit part of HVAC system for large commercial building.

Maxim has a variety of position sensing and signal conditioning solutions including proximity sensors (MAX44000), variable-reluctance sensor interfaces (MAX9924), and Hall-effect sensor interfaces (MAX9621).

Air Handling Unit (AHU), Rooftop Unit (RTU), Makeup Air Unit (MAU)

An AHU, RTU, or MAU conditions and circulates air as part of the HVAC system, which can include heating, cooling, humidification/dehumidification, mixing, fans or blowers, and filtering. AHUs are typically found inside buildings and have large capacities. Large AHUs usually contain a squirrel cage blower driven by a 3-phase AC induction motor to move the air. VFDs are available for higher efficiency units. Very large units can have multiple blowers. Filters, dampers, mixing chambers, and heating and cooling elements are the other key components. The heating and cooling elements of large AHUs are coils. These coils have fins, which create a large surface area. A central boiler or chiller plant supplies the coils with hot water, steam, or chilled water. Through the fins in the coils, this hot or cold water or steam is effectively released to warm or cool the air. Mixing chambers use dampers that alter the mix of fresh outside air with return air from the system. If the temperature of the outside air is close to the desired room temperature, the damper can automatically alter the mix of outside and return air to achieve the desired heating and cooling. By doing this, the central boiler or chiller plant does not need to provide steam or cold water, which lightens the load on these systems.

RTUs are smaller self-contained units with complete internal refrigeration and heating capabilities. They have

a fuel-burning capability for heating and a refrigeration unit for cooling.

MAUs differ from AHUs in that they use only fresh outside air. They do not use return air from the building. These are often used for commercial kitchen ventilation, laboratory ventilation, and anywhere large amounts of fresh air are needed to replace contaminated air.

Sensors for these systems include air flow, inlet and outlet air temperatures, air pressures at various points such as across filters, coil temperatures and pressures, humidity sensors (DS1923), and fan speed sensors (see *Position Sensors* in the *Recommended Solutions* table at the end of this chapter). Controls include pump and blower motor-speed commands to the motor drive, heater controls for RTUs, AC controls, humidifier controls, and damper settings. Filter replacement needs are detected by measuring the pressure drop from the input side to the output side at a nominal air flow rate (see the *Pressure Sensors and Weigh Scales (Force Sensing)* section in the *Sensors* chapter).

Variable Air Volume (VAV) Units

A single VAV unit typically supplies heating or cooling to a number of zones. Each zone has an air terminal unit that, under thermostatic control, opens or closes as needed to allow a variable flow rate. The VAV unit usually gets its air supply from an AHU. VAV units in cooling mode typically cool the air to a fixed temperature (55°F, 13°C) while having the ability to vary the flow rate using variable-speed motor drives. The combined effect of these terminal units flow restriction results in a total flow rate needed through the main plenum from the VAV unit. The main plenum pressure is simply sensed and controlled to a constant pressure by varying the speed of the VAV unit's blower.

Legacy pneumatic controls have largely been replaced with electronic controls, digital communication, and networking to the BAS.

Motor Considerations

Fan and blower motors have traditionally been the AC induction type (when 3-phase AC power is available) and VFDs to control their speed; their efficiency is quite good, but efficiency loss is still experienced when the motor is run at less than full speed and less than full power. The situation is even worse when 1-phase AC power is all that is available for small air-conditioning units. To attain different speeds, use motors with multiple taps or silicon-controlled rectifiers (SCRs). Either device will delay the power pulse to the motor for each AC cycle. However, both are less efficient. Because of this, BDC motors are increasingly being used. They offer both highly controllable speeds and high efficiencies over a wide speed and load range. They are also simple in construction, with only the controller portion being complex. Of course, the AC line needs to be rectified, but this is quite simple and inexpensive to do with diodes and a capacitor.

Constant Air Volume (CAV)

VAVs are replacing CAV systems due to the former's higher efficiencies in large installations, but CAVs are still found in smaller installations. Single-speed motors in CAVs provide constant rates of air flow, but the temperature of the air varies. There are several methods to control the air temperature, one of which is mixing cooled air with heated air in varying proportions.

Fan Coil Unit (FCU)

An FCU is a lower installed cost alternative to central heating systems and their associated duct work. FCUs are stand-alone room units that contain a fan, coil (for heating or cooling), electrical power, and fuel-supply connections. Simple thermostatic control is common, with no connection to any central BAS. However, connection is possible if communications interfaces are provided.

Humidifiers

Humidifiers are often needed in cold climates where the outside air is very dry due to moisture condensing (and freezing). Increasing the humidity can save energy. Because humid air feels warmer than extremely dry air, room temperature does not need to be as high. Humidifiers can use a variety of methods such as evaporative water trays, ultrasonic water atomization, and steam generation "vaporizers." Hard water causes issues for all types of humidifiers. As water is converted to steam in evaporative humidifiers and vaporizers, a residue accumulates in the water reservoir as scale deposits. Atomizer types send the hardness, and any pathogens, into the air along with the water, which, when the water droplets evaporate, causes the calcium dust to settle out and accumulate on anything nearby. Distilled water or water softening mitigates these problems. Also, sensors are needed for water level and humidity detection. In building-sized HVAC systems, steam is often available and this sterile source of humidity can be added in controlled amounts as needed. However, as with other types of humidifiers, hard water creates challenges.

Dehumidifiers

Dehumidifiers use mechanisms very similar to refrigeration units. They temporarily chill the air, which causes the moisture to condense and be collected, followed by the air being re-warmed from the condenser heat that was extracted. Then the dried, re-warmed air is simply sent back into the room. The water extracted is "distilled" water of high purity, but low volume in all but the largest systems in very humid climates. It is often simply discarded.

Air Quality Monitor

Monitors of various types are needed in homes and buildings to protect the occupants' health and safety. Stagnant air can cause the spread of sickness and allergies. In cases of high humidity, insufficient ventilation can promote the growth of bacteria and fungi such as molds.

Smoke detectors are the most often seen air quality monitors in homes and hotel rooms. Now carbon monoxide detectors are required by law in California in dwelling units, especially rentals, that have (1) a fossil fuel-burning heater, appliance, or fireplace (for example, a gas stove or water heater), or (2) an attached garage.

HVAC systems used in BASs monitor CO_2 levels to ensure that enough air is injected from the outside to keep CO_2 sufficiently low and oxygen levels sufficiently high. Other poisonous gasses may need to be detected in various industries to assure worker safety from fumes of toxic chemicals, particulates, and other airborne pollutants (volatile compounds, combustion products, radioactivity, etc.). The instruments and technologies used for detecting these pollutants vary widely and will not be covered here, but the outputs from these detectors are often tied into HASs or BASs. The responses to these detectors may be as mundane as HVAC system adjustments to increase outside airflow, or they may trigger alarms and response tied into the fire alarm system and/or other emergency response systems.

Specialty filtering and ventilation for some industrial processes are critical to the success of the process. Clean rooms for integrated circuit manufacturing are a prime example. The outside urban environment typically contains 35,000,000 particles per cubic meter that are 0.5µm and larger. This corresponds to an ISO 9 clean room. An ISO 1 clean room allows no particles at all in that size range, and only 12 particles per cubic meter of 0.3µm or less. To meet these standards, HVAC systems with special filters are needed. Some clean rooms also control humidity to low levels, necessitating the use of ionizers to prevent ESD problems. Air locks, air showers, and positive pressure systems are also used to maintain the air quality standards needed for some clean rooms.

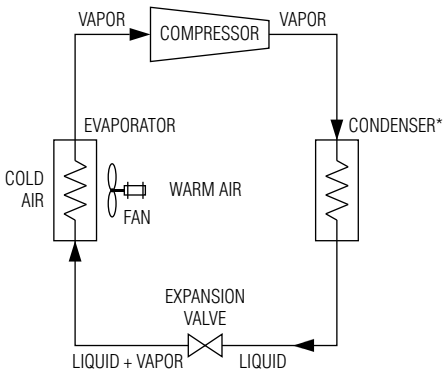
Detectors of minute quantities of anything typically produce small, high-impedance signals that require high amplification before being digitized. Since noise and offset are always amplified along with the signal, a very precise amplifier with low input offset voltage and low noise is needed at the front end of the detector. (If the noise and offset are high frequency, a DC-blocking capacitor can be used, but noise and offset are usually **not** high frequency in these types of systems.)

Maxim has several new op amps to address these needs. The MAX9632 single op amp, for example, or the MAX44251 dual op amp offer extremely low input noise and offset voltage while operating over wide supply voltage ranges.

Refrigeration

Mentioned earlier as a part in several systems, a refrigeration unit can be used to cool air temperatures, or it can be a stand-alone refrigerator or freezer for cold storage. No matter what the size or intended use, the fundamental operating principals are the same.

Compressor-based refrigerators, which use the "vapor-compression refrigeration" cycle, are very common in the homes and commercial establishments of developed countries. In contrast, the "absorption refrigeration" cycle is used when waste heat is available or where electricity is not reliable or available. The latter is also silent, whereas the compressor running the vapor-compression cycle can produce significant noise during operation. In large industrial plants, gas turbines to generate electricity and hot water, and the "waste" heat can be used by absorption refrigerators. When all three of these are generated by a single plant—electricity, useful heat, and useful cooling—it is called trigeneration. Cogeneration is the simultaneous generation of electricity and useful heat that can be the source of heat in district heating systems, for example. Large district heating systems are found in Scandinavia, Eastern Europe, and New York City.



*CONDENSER CAN BE WATER-COOLED OR AIR-COOLED.

Single-stage vapor compression refrigeration cycle.

Vapor-Compression Cycle

Vapor-compression refrigeration uses a refrigerant that transitions between a liquid and a gas at temperatures and pressures for the particular refrigeration application. In general, when a liquid turns into a gas through evaporation, significant quantities of heat are drawn from the surroundings, thereby cooling the area. Conversely, when a gas condenses into a liquid, the "heat of vaporization" is released back into the surroundings, which warms up. By using a power source to run a compressor, the heat can be forced to flow in the opposite direction from its natural flow from warmer regions to cooler regions. This is essentially a "heat pumping" process. Heat pumps use the same refrigeration cycle as air conditioners and refrigerators, but instead, they retain heat to warm an interior space and emit cool air into an exterior area.

The refrigerant is in a closed loop. In the first step, gas is compressed in the compressor, resulting in a high pressure vapor—the vapor-compression cycle. Because it is compressed, this vapor has an elevated temperature. It then enters a condenser where the vapor is cooled by either water or air, causing the gas

to condense. The heat generated by the vapor is often discarded. However, in some systems the heat generated is later used to warm water, or used to reduce the energy required to heat water for DHW or other uses. In a heat pump, this heat is used to heat a home.

The liquid refrigerant, still under high pressure, enters an expansion valve that allows only a slow flow of liquid to escape, keeping its inlet side at high pressure. The outlet side is at low pressure where the liquid enters the evaporator and is exposed to warm surroundings, usually warm air flowing over the evaporator coils where low pressure and warmth causes the refrigerant to evaporate. This evaporation absorbs large quantities of heat, so the air is cooled as desired. In a heat pump for a house, the same cycle is used, but the cold air is pumped outside while the heat generated is used to warm the interior.

Absorption Refrigeration Cycle

The absorption refrigeration cycle is a bit more complex. It uses a refrigerant that vaporizes at a very low temperature and, as in the vapor-compression cycle, this evaporation draws away the heat. The main difference is that, in transforming the vaporized refrigerant back to a liquid, heat is used and the process is silent. In this part of the process, the vaporized refrigerant is "absorbed" or actually dissolved into another liquid that has a high affinity for it. This reduces the vapor pressure of the refrigerant vapor, allowing more to evaporate. The refrigerant-laden liquid is then heated by the heat source, which drives the refrigerant out of the liquid. It then enters a heat exchanger where it is cooled to room temperature; due to the high pressure, it condenses back into a liquid where it is returned to the evaporator, completing the cycle.

All these systems on an industrial scale need sensing, monitoring, and controls for pump motors, valves, fans, blowers, etc., as well as safety systems to ensure proper shutdown under fault conditions. Controls must obviously respond to remotely sensed temperatures, pressures, and flow meters that are often long distances from the compressor and related equipment. Wireless communication is increasingly common, especially in homes where distances are relatively short.

Maxim has a variety of temperature sensors with digital interfaces enabling precise communication over longer distances than analog sensors. For more information on other sensor types and sensor conditioning functions, see the *Sensors* chapter. For industrial HVAC installations, PLCs or similar control equipment is used to communicate over fieldbuses. Maxim has many offerings in this area. See the *Programmable Logic Controllers (PLCs)* chapter for more information.

Lighting Control Systems

Lighting systems for area lighting or individual room lighting are used to enhance occupants' experiences and to save energy by turning out lights when rooms are vacated or when light from outside is sufficient to dim the lights. In addition to responding to occupancy, area lighting can also be controlled based on the time of day, the day of the week, or the occurrence of a special event. These lighting types enhance occupants' experiences when the space is used for different activities. For example, a restaurant will use dim warm lighting during dinner but brighter lights during breakfast and lunch; when it is time to clean and maintain the restaurant, very bright lighting may be used.

Expanding use of LEDs for a wide variety of lighting applications is helping to put downward pressure on their price. While their initial cost per lumen is still significantly higher than other lighting technologies (incandescent and cold-cathode florescent lamps (CCFLs), for example), their much longer life and higher efficacy make their operating-life cost significantly lower than the established technologies. As the technology continues to evolve we will see higher efficacy (lumens/watt) and longer lumen maintenance (% of brightness remaining after time), which continues to add to the number of applications for which their use is justified. This efficient, environmentally friendly, long life and rugged lighting technology will continue to improve our lives in many ways.

Maxim recognizes this important market by offering many products that drive all kinds of LEDs. Our products provide communications capability to control area lighting remotely and autonomously. For more information, refer to our *LED Lighting Solutions Guide* at: www.maxim-ic.com/lighting.

Room Automation

Many homeowners are connecting their audio/video (A/V) systems to their HAS. In commercial buildings such as schools, hotels, office buildings, lecture halls, conference rooms, board rooms, museums, and theaters, room automation systems (RASs) control the lighting and A/V systems, which enhance the audience's experience of everything from simple presentations to complex stage productions. The A/V equipment (video conferencing, video projectors, lighting systems, public address systems) falls under a different market segment (consumer and professional A/V equipment), but the control systems for this equipment are within this subset of the environmental automation segment. The control equipment involved includes dedicated computers, lighting controls, and related controllers to turn on and off ceiling-mounted projectors and the teleconferencing equipment.

Because the scope of RASs is a single room, wireless communication is very viable. Many systems set up a wireless hub and with wireless transceivers placed on each piece of equipment; they all gain a network presence and can be controlled from a single computer. With advanced applications programs, the sequence

of events and the corresponding lighting and A/V equipment needs are preprogrammed so that, as an event progresses, the operator simply triggers the next settings as needed.

Similar systems are available for the HAS that can control everything from lights, temperature, A/V components, TV/movie playing, and even powered drapes. With occupancy sensing and response, lights can be programmed to automatically come on when you approach and turn off, with some delay, after you leave. With phone-call sensing, TV and A/V systems can be muted when a call comes in.

Sensors needed include ambient light and proximity sensing (MAX44000) and remote wireless transceivers (see the *Wireless Systems* section in this chapter). They may derive power from energy harvesting (MAX17710) and charge batteries for high pulse loads as needed when they transmit, while eliminating the need to replace batteries. This means no wires and no battery replacement. Alternatively, if the equipment is wired to the Ethernet and if it draws low power, power over Ethernet (PoE) provides a convenient installation alternative, especially if Ethernet cabling is already installed (go to: www.maxim-ic.com/power-over-Ethernet). If not installed, communication can also be accomplished with powerline communications interfaces (go to: www.maxim-ic.com/powerline).

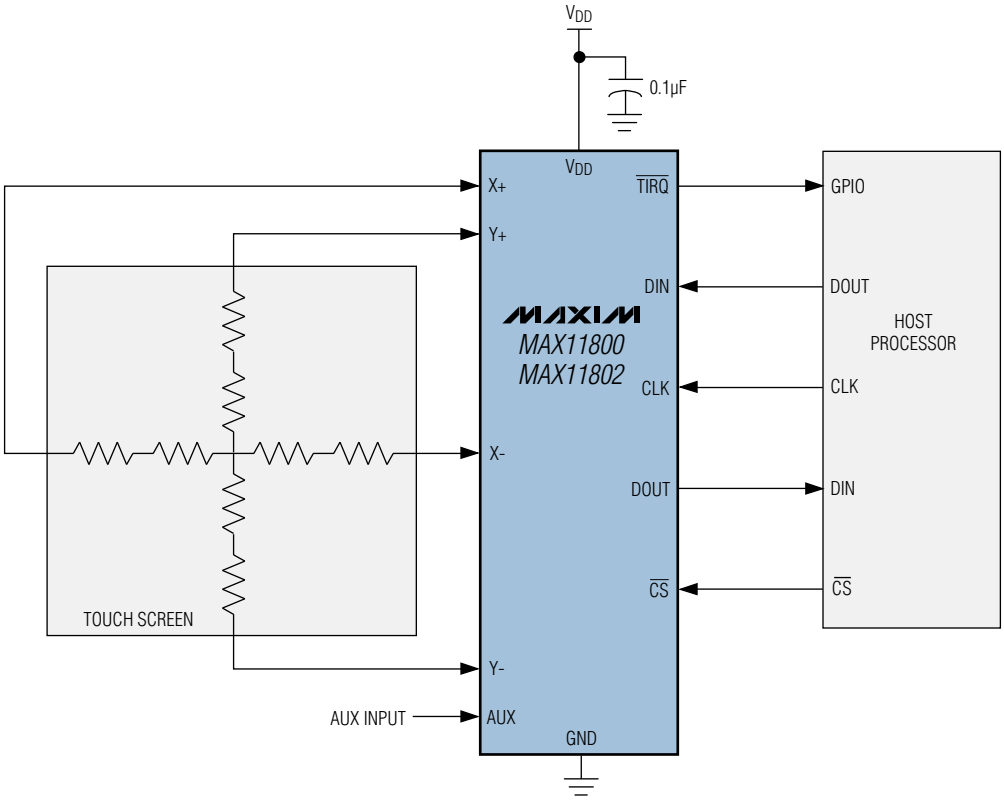
Simple to Implement Resistive Touch-Screen Controllers Reduce µP Overhead

MAX11800–MAX11803

The MAX11800–MAX11803 low-power touch-screen controllers operate from a 1.70V to 3.6V single supply, targeting power-sensitive applications. The devices contain a 12-bit SAR ADC and a multiplexer to interface with a resistive touch-screen panel. Digital preprocessing and the smart interrupt function generator greatly reduce the frequency of interrupt servicing required from the microprocessor. Autonomous mode further reduces overhead by allowing repeated scans. The on-chip FIFO stores the results until read by the microprocessor. Results are further categorized as "initial touch," "continuing touch," or "touch release."

Benefits

- Enable sophisticated touch-screen panels with minimal processor overhead
  - Digital preprocessing of touch events
  - Autonomous mode and FIFO allows multiple touch capture between µC interrupts
  - Touch categorization further frees system microprocessor processing
- Designed for reliable operation in harsh environments
  - -40°C to +105°C operating temperature range
  - 4-wire reliable touch screens supported
  - 25MHz SPI interface
  - ±8kV ESD protected inputs (X+, X-, Y+, Y-)



Typical application circuit for the MAX11800, MAX11802 resistive touch-screen controllers. Very few external parts are needed.

Building Energy Measurement and Management

In the days of abundant, low-cost energy, the consumption of energy to run a building was treated as an unavoidable and unmanaged expense. But energy prices continue to climb relentlessly and energy use increases in response to the expanding population of urbanized citizens. As a result, building operators and international organizations are focusing on this large use of energy and responding by seeking ways to reduce costs and resource consumption. The challenge is to reduce energy use while maintaining quality of service to the building's users.

As with any challenge, information provides a window into the process, highlights the best opportunities for improvement, and allows tracking of the results.

Electrical energy has the highest cost per kilowatt-hour of any form of energy used in buildings. The costs easily justify its measurement and management. Air conditioning systems (HVAC&R) and several other building systems such as elevators and escalators use powerful electric motors to run the pumps, fans, and equipment, consuming very significant amounts of electrical energy in the process. Power companies meter the total energy delivered into a building and submetering is provided for multiple-tenant buildings, but greater granularity is justified when individual components of a building's systems draw significant amounts of electrical power, especially when these components can be managed to modify their consumption.

The generation of usage data on subsystems in the building and subsequent analysis of usage history and trends give operators concrete information to manage energy consumption. With this data, one can quickly see where the bulk of usage is occurring, and this can lead to effective measures to reduce consumption, possibly by changing usage habits. For example, should the escalator continue to run when nobody is on it? Should the hotel room lights

Small power distribution and circuit breaker panel suitable for incorporation of energy measuring module.

remain on when the guest leaves? Should the air conditioner in a room start prior to a scheduled meeting?

Effective measuring of energy consumption can also possibly reveal the need to replace old, inefficient equipment with newer designs. This data can catch faulty systems that are drawing excessive power beyond their nominal levels. Moreover, the data can be used to qualify for LEED credits, ISO 50001 certification, and time-of-use billing adjustments.

Maxim has the technology to precisely measure electricity usage wherever desired, which can provide the information needed to treat energy consumption in buildings as a manageable cost while maintaining quality of service. Maxim's 78M6618 octal power and energy measurement IC can do this. The part measures up to eight single-phase AC lines. The 78M6613 is a single-circuit version that can be imbedded into individual equipment, giving it the ability to measure and report its own power usage. For more information on Maxim's energy measuring capabilities, go to: www.maxim-ic.com/energy-measurement.

Security Systems

Security systems include access control, intruder detection, alarms, and surveillance. Prior to automation, security for the home relied on door and window locks, and possibly a dog. Commercial establishments used security guards and doormen with keys for multiple mechanical locks. Surveillance consisted of security guards "walking the beat." The shortcomings of this system are several: the need of many people, the predictability of surveillance routes and times, and the duplication of keys.

Everything changed with the advent of modern electronics, networking, and video cameras. Access control is handled automatically, no people are required to open locks for others, security is pervasive with "someone always watching" the entire premises, and accounts are enabled and disabled quickly.

Access Control

Access control may now be implemented in a variety of ways. Individuals entering a building interface with the automated system using Wiegand keycard readers, keypads (resistive touch-panel controllers like the MAX11800 can be used as keypad scanners to avoid the use of mechanical switches, which are costly and wear out quickly), RFID keys (MAX66140), serialized iButton keys with authentication (DS1961S), magnetic stripe cards, or through some other method such as biometric authentication using fingerprint readers or iris scanners. The systems needed for these door-access devices include the appropriate sensor, signal processing (i.e., amplification, filtering, ADC), digital processing to extract the information that will eventually be compared to a database, data encryption, and, in highly security access points, security managers (DS3600) in the door devices. To send the data to the BAS, data transceivers interface with networks as well as more transceivers and computing systems

such as PLCs or industrial computers (see the *Programmable Logic Controllers (PLCs)* chapter). These transceivers and computing systems manage the data and feedback commands to open (or not open) the door's electric strike. Some companies are running Internet protocol to each door and providing power by PoE (like the MAX5980 and MAX5969D), which means that the door only needs a single CAT5 cable.

Intrusion alarm systems include glass-breakage detectors, laser beam detectors, door open/shut sensors, and occupancy sensors of various types such as motion detectors that use infrared (heat sensing), acoustics, magnetic sensing, capacitive sensing, inductive sensing, radar, or video image processing to trigger alarms. Many of these sensors produce a simple binary signal (e.g., intruder detected or not detected), and the sensor modules simply either close a relay contact or send a wireless signal that an event has occurred (see the *Wireless Systems* section in this chapter). To completely free up a wireless sensor, the batteries can be rechargeable types and power can be supplied from energy harvesting. The approaches are many, including solar, acoustic, vibration, and human energy such as pressing a light switch pressing, pushing a door, walking on a floor mat, etc. The MAX17710 energy-harvesting charger and protector is ideal for managing these sources and for charging and protecting the battery.

Once triggered by detected events, alarm systems are either silent, to catch trespassers in the act, or loud, to scare off trespassers. Calls can be automatically placed to security guards or security companies contracted by the building or home owners.

System control can be stand-alone or part of the BAS. Older systems needed many inputs because a star topology was used. In this type of topology, each sensor is separately wired into the control panel. These systems have mostly been replaced with "perimeter" wired systems. In these systems, a single cable encompasses the perimeter of the area to be protected. Each sensor in the system has a unique address on the bus.

RFID keycard and scanner for secure access control.

Wireless links between the sensors and the controller reduce the cabling required. This lack of cabling makes implementation of security systems for existing homes and small buildings easy. For more information, see the *Wireless Systems* section in this chapter.

The output of the motion detector can be used as part of an occupancy-response system. During normal business hours, the motion detector can turn on lights as needed. After hours, the motion detector serves as the sensor portion of the security system. The BAS can control which function prevails based on the time of day and day of the week. Also, because one device, the motion detector, can be used for two functions, occupancy-response or sensing, installed costs are lower.

The sensors in the security system can also sometimes be used to detect fire or smoke, and thus are often tied into the fire protection system.

Surveillance

Surveillance systems include cameras, communications interfaces, video recording systems, and display terminals. These electronic systems require just a few security guards to constantly monitor entire facilities. Recorded images are constantly improving in quality and often serve as critical pieces of evidence in trials. Improved video quality, increased numbers of cameras, and more recording time are all goals of surveillance systems. Maxim's video products group has a variety of products to address these goals. For more information, go to: www.maxim-ic.com/security.

Battery backup of security systems can ensures security even in the event of a power failure (or power shutoff by the intruder). Maxim has a variety of battery management products to address charging and monitoring needs (go to: www.maxim-ic.com/battery-management).

With networking capability built into security systems, homes and buildings can be monitored from anywhere in the world with Internet access; alarms can be sent to an Internet-connected device such as the homeowner's or security guard's smartphone.

Fire Alarm Systems

Fire alarm systems must detect fires, activate alarms, prevent false alarms and notify response teams. In homes, the minimum requirement by law is a stand-alone battery-powered smoke detector. However, many building codes require more advanced systems with smoke and heat detectors and automatic sprinkler systems.

Fire safety systems can not only turn on sprinklers where heat is detected, but also, by sensing water flow in the pipes, determine where the fire is and report this to related systems. If connected to a BAS, this event can trigger the system to automatically call the fire department and adjust HVAC duct dampers and fan settings to prevent the spread of smoke and fire. These automated systems greatly reduce the time it takes a fire department to respond. The BAS can also command elevators to return to the ground floor and disregard requests for use.

Equipment includes fire alarm control panels, which are the hub of the system. The panels communicate through various means with the BAS, and potentially directly with the fire department in some larger facilities. They take inputs from the many sensors and switches in the system such as smoke and heat detectors (MAX6682), detectors of by products of combustion (carbon monoxide and other gasses), flame detectors (MAX44006* RGB color sensor, MAX31855 thermocouple-to-digital converter), detectors of emergency door use (MAX9621 Hall-effect sensor interface), and manually activated fire alarm pull stations, and then respond in several ways. Activation of the fire alarm response includes sounding alarm bells or sirens; activating strobe lights (MAX16821 HB LED drivers), exit lights, and sprinkler systems; and manipulating HVAC system duct dampers, lighting, and human transport systems, such as doors, elevators, and escalators. In factories, the fire alarm response may shut down some processes and activate others, such as emergency backup power generators.

Backup Power Systems

In some buildings, the loss of grid power can be a critical event. Diesel generators, battery banks, flywheels, etc., can all serve as sources of power for varying periods of time until utility power is again available. Some facilities can suffer a few seconds of complete power loss until diesel generators are powered up and put online. But some critical facilities are unable to suffer **any** power loss, so they incorporate battery banks, flywheels, or other means to provide a few seconds of power until the generators are online.

Controllers for backup system startup and switchover include powerline sensing, load sensing, computation, and signaling. Many of these functions can be provided by off-the-shelf Maxim parts, but the requirements vary widely, so these functions will not be discussed here. Precision, high-speed, and robust signal processing is a general requirement that can be addressed by many Maxim products found in this guide.

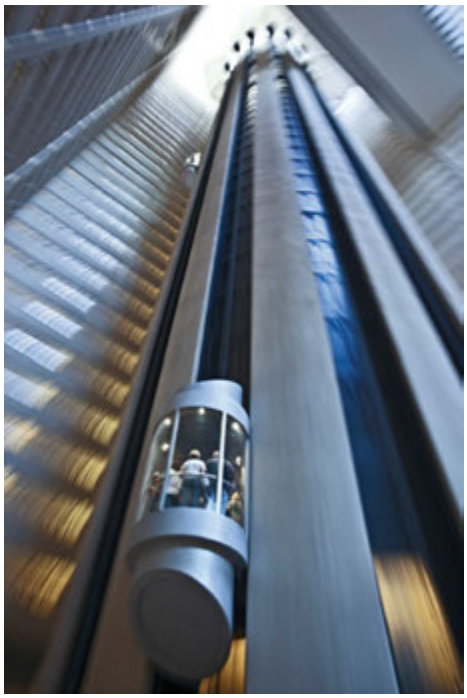
Elevators, Escalators, and Moving Walkways

Elevator

The building elevator (or lift) is the vertical transporter for people and freight in multiple-story buildings. The smallest elevators ("dumbwaiters") are used for freight or food service between floors. Elevators can carry large groups of people or pallets of freight. The largest to date can carry 80 people or over 11 thousand pounds (5000kg). In large buildings, such as hotels or office buildings, elevators are usually driven by electric motors and cable systems, but in buildings with approximately less than seven floors, elevators use hydraulic cylinders and pumps.

With the advancement of elevator technology and the importance of elevators in high rise buildings, the elevators now use electronic controllers with significant computational capability. During rush hours, multiple requests for the elevator can occur simultaneously from multiple floors. The controller must allocate elevator resources accordingly among multiple elevators, if there is more than one in the facility, and within each elevator in the system. Requests from outside the car and from inside the car all impact the resultant operating parameters such as direction, acceleration and deceleration rates, top speed based upon expected distance, and timing of responses to new requests based on car location and current speed.

Depending on the use of the elevator, controllers adjust the movement of the elevators. A hospital elevator moving fragile patients may need to start and stop very gently, while a freight elevator may need to handle extremely heavy loads slowly. An express elevator in a skyscraper may need to accelerate to high speed to reach upper floors quickly. Hotel elevators may need to provide a good compromise between speed and comfort. The control algorithms are usually based on "Up Peak Round Trip Time" calculations described in the *Guide D: Transportation systems in buildings* of the Chartered Institute of Building Services Engineers (CIBSE).



Modern elevator in high-rise building.

In the event of fire or other emergency, elevators are usually commanded to park at the ground floor and not to respond to requests for service. Yet some emergency elevators are employed for people with disabilities.

AC induction motors driven by VFDs provide a convenient system to provide the required variable torques, accelerations, and speeds under widely varying loads as users and freight come and go. With the use of regenerative VFDs, deceleration forces can be created by the VFD pumping electrical energy back onto the grid, thus saving energy instead of throwing it away as heat. Counterweights are often used to reduce the peak motor power required.

*Future product—contact the factory for availability.

This equipment and the main controller are usually in a machine room located at the top of the building. Alternatives exist where there are machine roomless designs where the motors are within the elevator shaft. These reduce space and equipment costs, but can be harder to service. Some potential exists for using linear induction motors and linear switched reluctance machines (LSRMs) for elevator applications.

It is critical that the elevator stop exactly at floor level, so various sensors can be used to assure this. To keep the elevator at this level as passengers come and go thus changing the weight, a brake is usually used on the motor shaft. This is a mechanical brake (drum type) that needs to be energized to release. Therefore in the event of a power failure, the brake is applied preventing the elevator from falling. Additional safety mechanisms can also be added to ensure that the elevator will not free-fall due to cable breakage. These are usually mechanical mechanisms that respond to loss of pull from the cables.

There is a set of doors on each floor and a set of doors that move with the elevator. At the floor, these open and close simultaneously so users hardly notice that they are not one set. Optical sensors and limit switches are used to coordinate their movements. Both doors' movements are usually driven by a motor mounted on the car roof. When the car is not at that floor, that floor's doors are securely locked. Of course the door closing process is also carefully controlled to prevent pinching items between the doors. Once all obstructions are gone, after some delay, the doors are closed gently. If the doors are kept open too long, a buzzer sounds to hurry people up. Some elevators (often freight elevators), for example, have two sets of doors on opposite ends of the car for easier access to loading docks.

In addition to the standard array of buttons that need to be sensed to select the floors, other sensors and input devices include card readers for restricting access to authorized card carriers only, elevator weight sensors, and environmental sensors for air quality (DS7505 thermostat, DS1923 humidity sensor). Small heating/cooling units are used on elevators to maintain occupant comfort (MAX31785 fan controller). There are various lighting needs for the floor select buttons (MAX16814 LED driver) current floor indicator display (MAX6966 display driver), overhead lighting and wall displays, speakers for background music, buzzers, and other needs. Emergency phones, fireman override controls, special "Code Blue" controls in hospital elevators, and security cameras (Maxim video products) round out the systems in the car.

Signals from the input devices are communicated to the elevator controller by various means from analog signals to binary levels to serial digital interfaces.

Overload sensing is one example of a closed loop in the elevator system. If an overload is detected, the controller does not allow the elevator to move until the weight is reduced below the limit. A buzzer or some other audible indicator of overload is activated in the car.

Commands from the elevator controller to the lift motor VFDs are usually in the form of RS-485, such as the MAX13448E RS-485 transceiver. The BAS communicates to the elevator controller if there are emergency override needs, such as from the building fire alarm system.

Escalators and Moving Walkways

An escalator is a moving staircase and a moving walkway is a horizontal moving surface. Escalators have much higher people-moving capacity than elevators, but require ambulatory riders. They generally connect floor to floor just like staircases, and are most often seen in department stores, transportation terminals, hotels, convention centers, and sports arenas. They can be installed indoors or outdoors if weatherproofed. The direction can be reversed either manually or automatically.

Moving horizontal walkways are made much like a conveyor belt with a flexible rubber or segmented surface connected in a long loop. Both escalators and moving walkways also have moving handrails that move (close to) the same rate as the stairs or walkway. Many of these systems run continuously during building operating hours, but some are programmed to stop if there are no users, thus saving energy. The stopping and starting must be gentle, and anticipating a new rider is a benefit so it is already moving when they get on. This can be accomplished with proximity sensing (like the MAX44000 proximity sensor).

Drive is usually provided by AC induction motors and VFDs. The use of regenerative VFDs saves energy from "down" escalators where the users' combined weight can play a significant role in feeding energy back into the grid to offset the energy needed for the "up" escalators.

Escalator floor openings present a fire propagation path risk so the under sides of the escalator truss is often protected with fire sprinklers or with fireproof panels. The motors themselves generate significant heat, especially for continuously moving escalators and moving walkways, so either dedicated HVAC systems or adequate ventilation is needed.

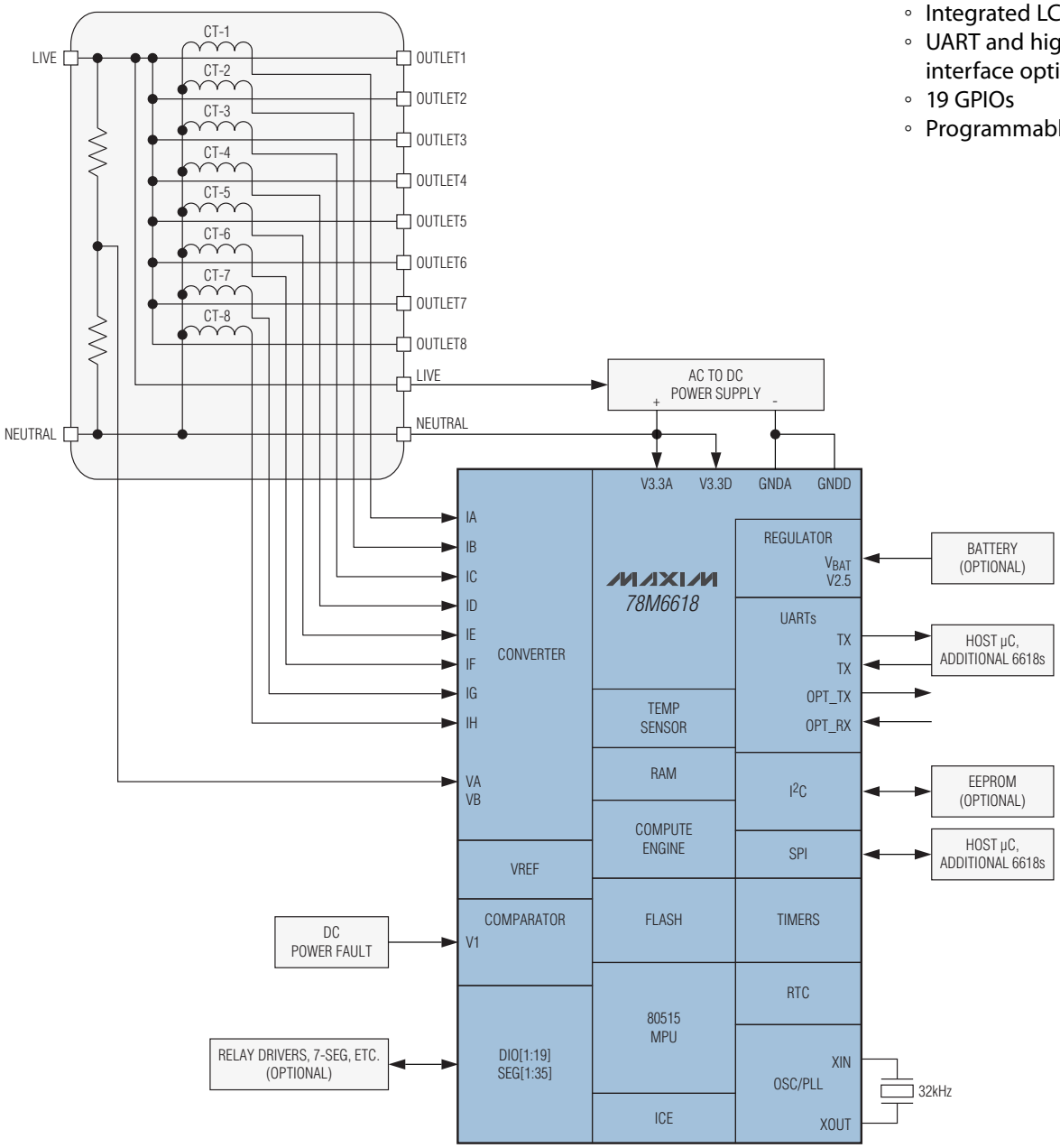
Octal Power and Energy Measurement IC Provides Accurate Data from Power Distribution Units

78M6618

The 78M6618 measures power from up to eight single-phase power paths, providing accurate usage data on eight branch circuits. The 32-bit compute engine and the 21-bit delta-sigma ADC provide accuracy beyond that required for metering applications. Temperature compensation and precision voltage reference keep accuracy in specification over the industrial temperature range (-40°C to +85°C).

Benefits

- Provides high-accuracy data on power draw on up to eight branch circuits with a single IC
  - < 0.5% Wh accuracy over 2000:1 current range over temperature
  - Power factor measurement
  - Exceeds IEC 62053/ANSI C12.20 standards
  - Accumulated Wh, kWh, and cost
- Integrated features enable an enhanced solution at low cost
  - Integrated LCD driver up to 70 pixels
  - UART and high-speed slave SPI host interface options
  - 19 GPIOs
  - Programmable alarm thresholds

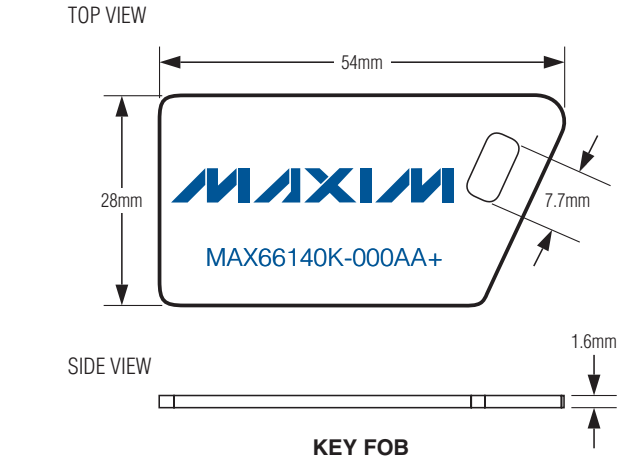


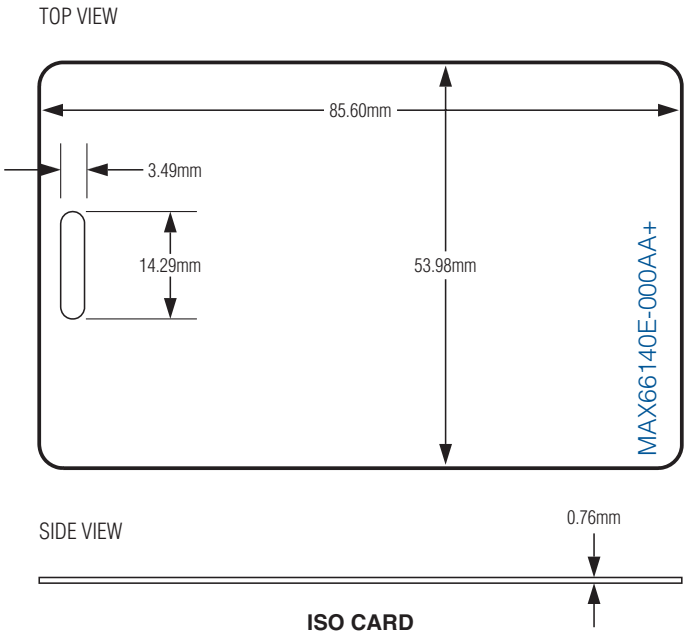
Typical application circuit for 78M6618 octal power and energy measurement IC.

RFID Keycard Meets International Standards for Data Authentication and Transmission to Provide Secure Contactless Entry Systems

MAX66140

The MAX66140 keycard secure memory complies with ISO 15693 RF interface and ISO 10118-3 SHA-1 authentication to provide secure contactless entry systems for buildings and protected areas of all kinds. It also provides asset tracking capability.





The MAX66140 comes as a key fob or as an ISO card.

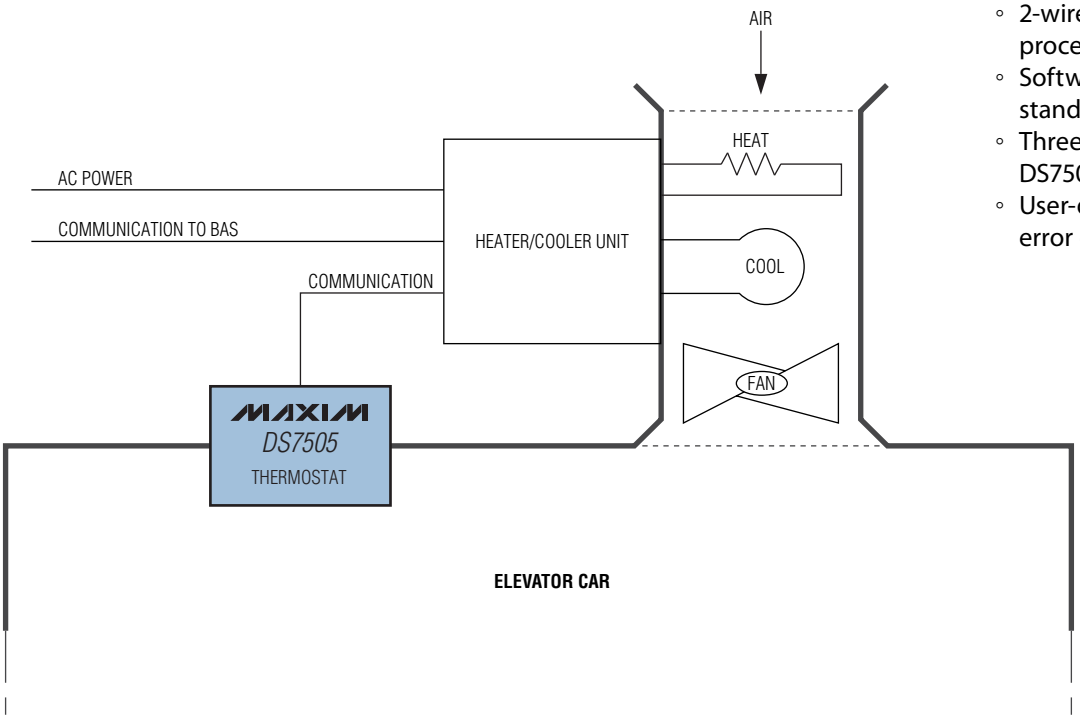
Benefits

- Provides high level of security at low cost
  - SHA-1 authentication with 64-bit secret prevents cloning
  - Unique 64-bit identification—no two keys are alike
  - 1024-bit user EEPROM for any integrator-defined data storage needs
- Provides durable and highly reliable operation
  - Fully compliant with ISO 15693 and ISO 18000-3 Mode 1 standard
  - 200,000 minimum write/erase cycles
  - 40yr minimum data-retention time
  - -25°C to +50°C operating temperature range

Add Programmable Thermostat Function to Any Equipment with Single IC

DS7505

The DS7505 is a single IC thermostat that offers high-precision, nonvolatile thresholds over a wide range of temperatures and user-programmable number-of-events filtering before tripping to avoid false alarms.



DS7505 thermostat used in elevator heater/cooler system. Communication to the BAS is only needed when changing the nominal temperature setting or when faults are detected. Normal operation is performed at the elevator car.

Benefits

- Very high-precision silicon solution spans wide temperature range
  - Operation over -55°C to +125°C
  - ±0.5°C accuracy from 0°C to +70°C
  - 9-bit to 12-bit digital temperature readings resolution
- Digital out simplifies design while maintaining sensor precision
  - 2-wire serial interface saves processor pins
  - Software compatible with industry-standard LM75 in 9-bit mode
  - Three address pins allow up to eight DS7505s on same bus
  - User-defined number of consecutive error conditions before flag is set

Hierarchy

As mentioned at the beginning of this chapter, BASs are truly DCSs made up of a networked collection of controllers, some specialized to a particular task near the bottom of the hierarchy while others, usually at the upper end of the hierarchy, are less specialized and more generically capable of handling traffic over standard industrial interfaces. The similarity to factory control systems is more than coincidental. Due to the wide use of standard equipment and interfaces in industry, the less specialized equipment is very readily available and experts in their programming and use are also widely available. Taking the comparison a bit further, the primary bus shown in the diagram below is analogous and potentially identical to the Industrial Ethernet backbone in a factory automation system. For BASs, standard Ethernet may suffice since the time determinism of Industrial Ethernet may not be needed. The secondary buses shown are analogous to the fieldbus. The main differences are that the these secondary buses are most often implemented using BACnet, a data communication protocol for building automation and control networks, and LonTalk® from Echelon Corp., as the communications standard, which are tailored to BASs as opposed to other protocols found in factory automation systems such as PROFIBUS, Modbus®, ControlNET, etc. Note that all these communication standards can use RS-485 as the physical layer. BACnet and LonTalk do **not** specify what the physical layer must be.

Controllers

Because some controllers are very generic, see the *Programmable Logic Controllers (PLCs)* chapter for details on these general-purpose controllers. For this chapter's discussion, much of the equipment found in homes and buildings have their own built-in controllers with user interfaces for manual control and communications interfaces for connections to that equipment's controller as part of the BAS. These individual controllers built into the equipment do not require much in the way of big-picture control. They can simply focus on the basic running of that machine, leaving the BAS (through its controllers for that particular system to modify the machine's behavior) to implement more sophisticated control algorithms.

For example, the BAS is instructed by the building manager (a person) looking at his schedule for the day to start warming a conference room in preparation for a meeting two hours before it starts. He knows he can reduce his heating energy bill by implementing a slow heating cycle, and this is easy to do because the BAS has energy-savings algorithms built in so that it can be instructed to slowly increment the temperature set point for the room up to that temperature over a two-hour period, instead of immediately setting it to the final temperature. The room is temperature-controlled from a VAV unit that supplies heated air to the room through an automated terminal unit (TU) that has a motor-controlled damper. (This VAV may be relying on a steam feed from the boiler for its heat source, so the boiler must also be up and running in advance, but this is likely

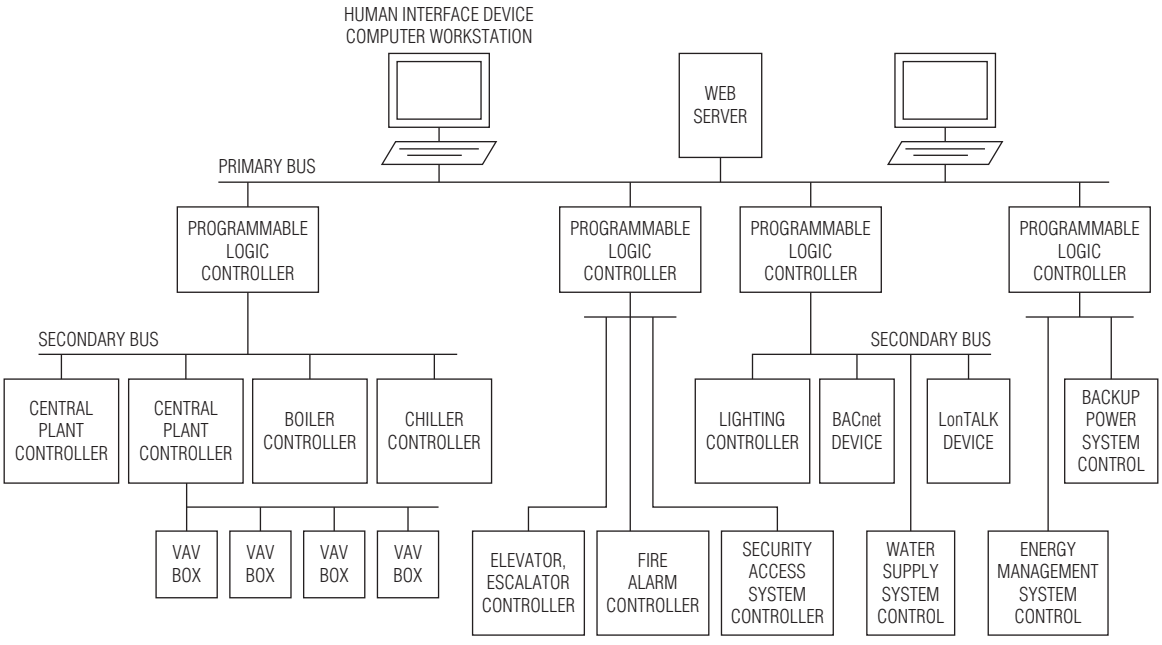


Diagram outlining the control structure for a modern BAS.

since its outputs are used for several other things.) Responding to the BAS, the VAV unit simply needs to generate a fixed temperature at its output plenum and is programmed to always set it to the maximum allowed room temperature. It also must keep the plenum pressure at a fixed level. As the room thermostat sees its set point moved up by a message from the BAS, it responds by requesting warm air from the TU. The TU receives the command to open the damper only a small amount since the temperature-error message is only a couple of degrees. The damper motor on the TU opens the damper slightly, which allows some warm air into the room; the VAV unit responds by increasing its fan speed slightly to maintain the plenum pressure. It then increments the heating a small amount to maintain its output temperature. As the room reaches the set temperature quickly, the thermostat is satisfied and the TU is instructed to close. This makes the VAV unit slow down its fan, and less energy is needed to keep the plenum warm. As the thermostat is incremented again, the process repeats producing small steps of temperature increase in the room. By slowly increasing the room temperature this way there is no overshoot and no massive amounts of heat needed to bring the room up to temperature quickly. Doing so is an overall lower energy method to warm the room, although it takes longer, but by starting the process early this is not a problem. This example shows that even though the VAV unit has its controller built in, its job is **not** to bring the room up to the final temperature. Its job is simply to keep the plenum temperature and pressure at a constant level. Similarly, the TU damper controller responds only to differences in temperature between the set point and the actual temperature, with no knowledge needed of the actual final temperature requested. And the thermostat itself is remotely controlled by the BAS instead of a person having to enter the room and make the repeated adjustments. There are certainly different ways to divide up an automation of processes like this, but this example demonstrates distributed control. Each controller has its limited, well-defined job that contributes to the overall control system, which can be quite complex and running sophisticated algorithms. But it is made up of many simple pieces with the result being, in this case, energy savings, predictable room temperature, and minimal human interaction needed to achieve these results.

Communications/ Networking (Wired/ Wireless)

BACnet and LonTalk

BACnet and LonTalk are two competing networking standards for building automation. They are used extensively for HVAC control, lighting, access control, fire-detection applications, and more. BACnet is under continuous maintenance by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Standing Standard Project Committee 135. The BACnet protocol defines a number of data link and physical layers, including ARCNET, Ethernet, BACnet/IP, point-to-point over RS-232, Master-Slave/Token-Passing (MS/TP) over RS-485, and Echelon's LonTalk, which is a rival protocol to BACnet. BACnet/IP and "Virtual LANs" allow for TCP/IP, ATM, etc.

BACnet creates the concept of an "object" and communication rules that make equipment from various vendors all communicate following the same rules. Any BACnet device is simply a collection of objects that represent the functions actually present in the real device.

The network structure is a client/server model. Messages are "services" that are carried out by the server on behalf of the client.

LonWorks and LonTalk

LonWorks® is a networking platform created by Echelon Corp. for control applications in buildings. LonTalk is the communications protocol. The protocol is also one of several data link/physical layers of the BACnet ASHRAE/ANSI standard for building automation. ISO and IEC have granted the communications protocol, twisted-pair signaling technology, powerline signaling technology, and Internet protocol (IP) compatibility standard numbers ISO/IEC 14908-1, -2, -3, and -4.

Optical Fiber

Many new buildings install optical fiber to ease high-speed networking capability. Because a single fiber can carry much more data than electrical cables, they are small, and glass is much cheaper than copper, optical fiber is an economical choice. Fiber is also immune to electrical interference and voltage surges, and there is no crosstalk between signals in different cables. They form a natural electrical isolation barrier since they do not conduct electricity. Additionally, optical signals can be used in explosive environments without added danger because they cannot cause any sparks. Of course, power is still needed for the optical transceiver.

A variety of modules provide transitions between electrical systems and the fiber links. Maxim offers several products for these modules. For details, go to: www.maxim-ic.com/optical-module.

Powerline Communication

Where it is difficult to run networking cable, there are now a variety of powerline communications technologies that provide robust data communications at high data rates over existing power lines. These new technologies overcome the problems of data loss due to noisy power lines and transformers blocking the signals.

Power over Ethernet

PoE technology enables power through switch/router in either midspan or endpoint systems, collectively named power-sourcing equipment (PSE), to deliver power over the data cable. The power-receiving system is called a powered device (PD). The PSE must detect and classify the PD successfully before powering it. Once the PD is powered, the PSE keeps monitoring for the PD disconnection and must power down the cable in approximately 350ms

once the PD is removed. The PSE must also protect the cable and the PD from overcurrent and short-circuit conditions. These protections in PoE provide unique safety and power-savings capabilities. PoE is becoming an option in a growing number of industrial applications due to new computing devices, lighting, sensors, and user-interface units all declining in power consumption. Furthermore, PoE standards are being expanded to support high power levels. By integrating all required functions, the Maxim PSE controller MAX5980 makes designing PSE systems simple, compact, and cost effective. PD equipment design is likewise simplified by the use of the MAX5969D.

PoE Specifics

Topology: Point-to-point

Maximum power at PD input: 12.95W of 3af standard, 25.5W of 3at standard, up to 100W of nonstandard

Data rates: Compatible with standard Ethernet data rates

Distances: 100m

Standards: IEEE® 802.3af, IEEE 802.3at

For more information, go to: www.maxim-ic.com/power-over-Ethernet.

Wireless Systems

In certain BASs it is simply not feasible to run wires to establish a communications link. The first two considerations in choosing the RF link technology are the link distance and the required data load. There are additional considerations, such as whether the communications can be one-way or two-way. Some applications such as video security, to be implemented wirelessly, require relatively high data rates and constant transmission. Other applications have very low data loads and require only periodic transmissions.

Systems that detect room occupancy are an example. Since channels handling low data loads use much less power than those with high data load, they can often be implemented using battery power while realizing manageable battery life. It is also possible to harvest energy from unconventional sources and use rechargeable batteries, thereby greatly reducing maintenance.

In home applications, distances are not usually very far and may be low data load, so radio power levels can be low. In large buildings, however, the distances become significant and the data load increases, so the capabilities of the wireless system must be greater. Maxim has a wide variety of radio technologies that solve unique engineering challenges and a high-frequency ASIC group that works with customers to develop proprietary solutions. For more information, go to: www.maxim-ic.com/asics.

Before discussing the wireless interfaces specifically, let us briefly explore the motivations behind implementing wireless communications. Why wireless, if it is fraught with problems?

Problem 1: Power. If you install a wireless link, you need to power both devices, so you need a remote power source. However, your main motivation for using a wireless link was probably to avoid wires, so unless there is a nearby power outlet, you need to rely on batteries.

Problem 2: Link range.There is no guarantee that the link will be established or be error-free because of EMI/RFI, walls with metal structure, or equipment blocking the signal and limiting the range.

Problem 3: Data security. Unless directional antennas are used, the information spreads out in all directions for anyone to pick up if they have the right equipment.

Despite the problems, there are significant benefits to using a wireless link with solutions to these problems.

Benefit 1: Ease of installation and modification. It is much easier (and probably cheaper) to install a stand-alone module than it is to run wires through walls or in ceilings; when the system needs to be expanded or modified, it is simple to do.

Benefit 2: Enables mobile applications.

Benefit 3: Enables a communication link across a barrier that is impossible to puncture with wires that would compromise the structure's integrity.

Let us address the first problem, power. In the case of a low data load application, one can avoid periodic battery replacement using Maxim's energy-harvesting technology (MAX17710) that can extract energy from a variety of sources such as light, vibration, thermoelectric, radio frequency energy, and varying magnetic fields. It manages the charging of a battery, a super capacitor, or microenergy cell. To get enough voltage for the battery, it boosts the voltage from low-voltage sources as low as 0.75V and it handles high-voltage sources up to 5.7V. It also protects the battery from overcharging and overload. Of course this energy-harvesting capability is not viable unless the average load on the battery is less than the energy available. Maxim has made significant progress reducing power waste in our radio solutions. In typical security applications, the radio transmits only periodically, and between transmissions enters sleep mode where power consumption is nearly zero. Therefore, if one were to use primary cell batteries needing periodic replacement, Maxim's radios help to extend the life of those batteries, or if using an energy-harvesting approach, can make it workable.

The second problem is link range. This is a fundamental task for all installers of radio links, to perform "link budget" analysis. All gains and losses from the transmitter to the receiver are considered and the final system must include some margin to assure reliable results. Several variables can be adjusted to achieve a successful outcome.

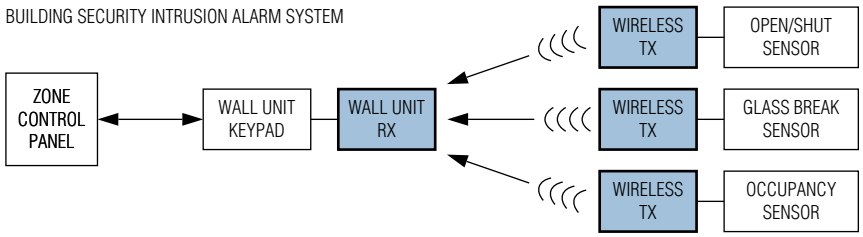
Transmit power, antenna gains and losses, transmission medium losses, receiver sensitivity, noise, interference sources, and other environmental factors can all have an effect. Errors in the data can be detected and corrected using cyclic redundancy checking (CRC) or more sophisticated algorithms, or a retransmission can be requested. Repeaters can be used to extend the length of the link. Maxim has some of the most sensitive receivers on the market providing extended link range.

The third problem is data security. A variety of methods can be implemented to protect data from unauthorized acquisition. Data encryption is the most applicable to this discussion, but other measures exist, such as CDMA and spread spectrum, but for simple ISM band radios using ASK, FSK, or OOK modulation, data encryption is the common method of securing the data. This is applied in the microprocessor in the system. The MAXQ1004 microcontroller incorporates AES encryption and a random-number generator to enable master/slave challenge-response authentication so data will not be transmitted until a valid link is found. Once found, the data will be encrypted, making it unintelligible without knowing the key.

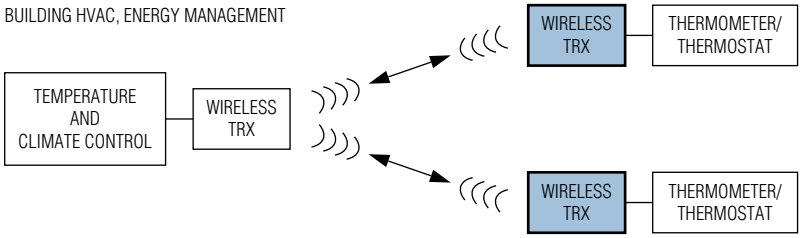
ISMRF (Industrial, Scientific, and Medical RF) Radios for Environmental Automation

ISMRF consists of low-power (5mA to 20mA, 3V) radios that work in unlicensed radio bands from 300MHz to 950MHz. They have been used in applications that require low duty cycle (0.1% to 10%) and low burst data rates (1kbps to 30kbps), such as remote car keys, garage door openers, home security, home lighting, window shade/curtain control, and TV remotes.

Many of the scenarios listed in this chapter can be served by these simple radio links. Depending on the needs and complexity, these links can be one-way (transmitter at one end and receiver at the other) or two-way (transceivers at both ends). The Maxim parts in these radios comprise, at the very least, an ISMRF radio IC and often a MAXQ® microprocessor.



One-way building security. Intrusion sensors (open/shut, glass break, motion, or IR) turn on the transmitter only when an alarm condition occurs. With one-way communication there is no way to check the status of the sensors or the transmitter remotely.



Two-way HVAC. Thermostat turns heater/AC on and off wirelessly via commands transmitted from the thermostat to the HVAC controller. The HVAC control center changes the thermostat setting on a nonperiodic basis via communication in the opposite direction.

The figures above illustrate two areas of environmental automation where these radios could be used: building security and HVAC. One configuration contains a one-way radio link and the other contains a two-way radio link.

Other Wireless Environmental Automation Applications

- Two-way building security. Intrusion sensor turns on its transmitter due to an alarm condition. Security controller interrogates intrusion sensor and checks for response indicating proper operation and battery health.
- One-way HVAC. (1) Transmitter on thermostat, receiver in heater or AC, replaces control wire. (2) Transmitter on heater, receiver in thermostat. Change thermostat setting at random times in a remote or closed area without sending someone inside.
- Storage facilities environmental control. Remote control center for outside storage area monitors temperature, humidity, air circulation, and light level, and sends commands to control systems to adjust each to maintain a particular environment.
- Hothouses for growing vegetables in the winter. Remote control center for outside growing area monitors air temperature, humidity, soil wetness, and soil pH, and sends commands to control systems to adjust each to maintain optimum growing conditions.

Specific Maxim IC Grouping

- One-way:
  - MAX7044 ASK Tx, MAX7036 ASK Rx, MAXQ610 microprocessors
  - MAX7057 ASK/FSK Tx, MAX1471 ASK/FSK Rx, MAXQ610 microprocessors
- Two-way:
  - MAX7032 ASK/FSK TRX, MAXQ1004 microprocessors

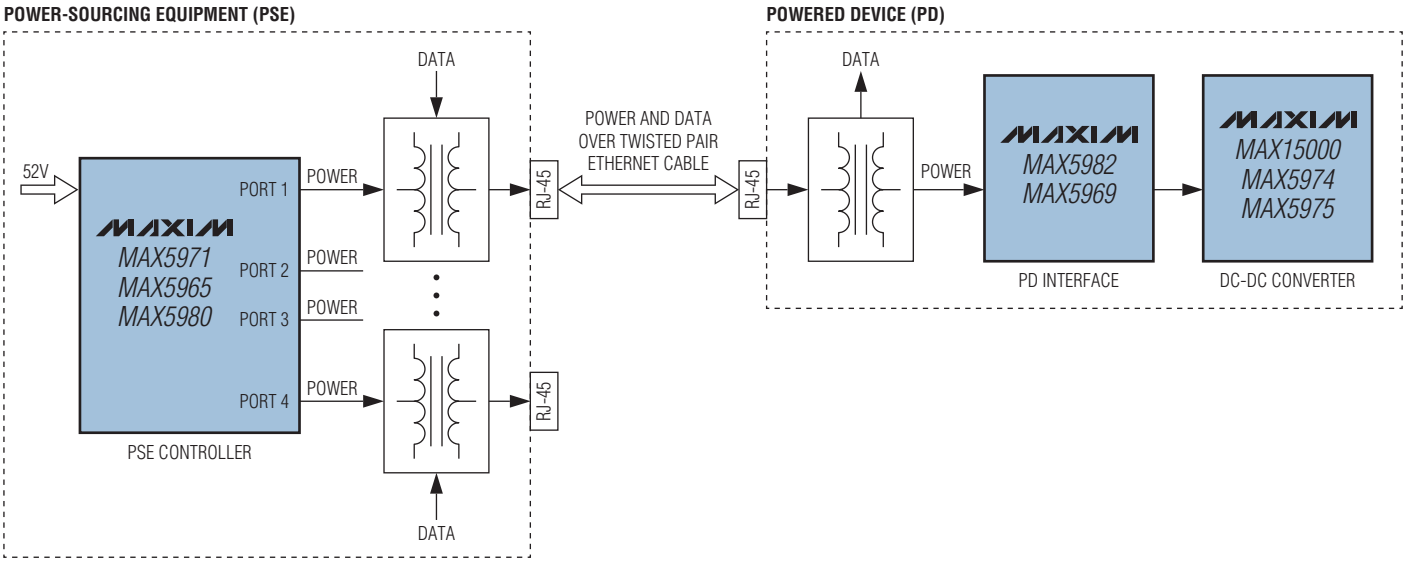
PoE Controllers at Both Ends of the Link Enable Power Beyond Standards While Lowering Power Loss

MAX5980, MAX5969D

The MAX5980 quad PSE controller and MAX5969D PD controller work together to allow power transfer beyond IEEE 802.3af/at standards. While the standard limits PSEs to 12.95W(af), 25.5W(at) per port, with the MAX5980 one can design PSEs to provide up to 70W/port, while offering the lowest power loss in the industry with only 0.3Ω channel resistance. The MAX5980 also meets PSE-ICM V2 requirements. On the PD end, the MAX5969D meets IEEE 802.3af/at requirements while being able to deliver more power than this standard to the equipment. Individual channels can provide up to 30W with the ability to be paired to provide up to 60W to the PD. The MAX5969D also features sleep mode to further save power during idle times.

Benefits

- Provide efficient power transfer while meeting current standards
  - MAX5980 meets IEEE 802.3af/at and PSE-ICM V2 standards
  - MAX5969D meets IEEE 802.3af/at standard
- Offer increased flexibility in equipment design by providing power capability beyond standards limits while lowering power loss
  - MAX5980 allows up to 70W/port in PSEs
  - MAX5969D allows up to 60W PDs when 2x2 pair configuration is used
  - Keep power loss low with MAX5980's low 0.3Ω channel resistance and MAX5969D's low I/O leakage (< 10µA)
  - MAX5969D's sleep mode lowers power usage during idle times



PoE system block diagram. Several complete reference designs are available for PoE applications.

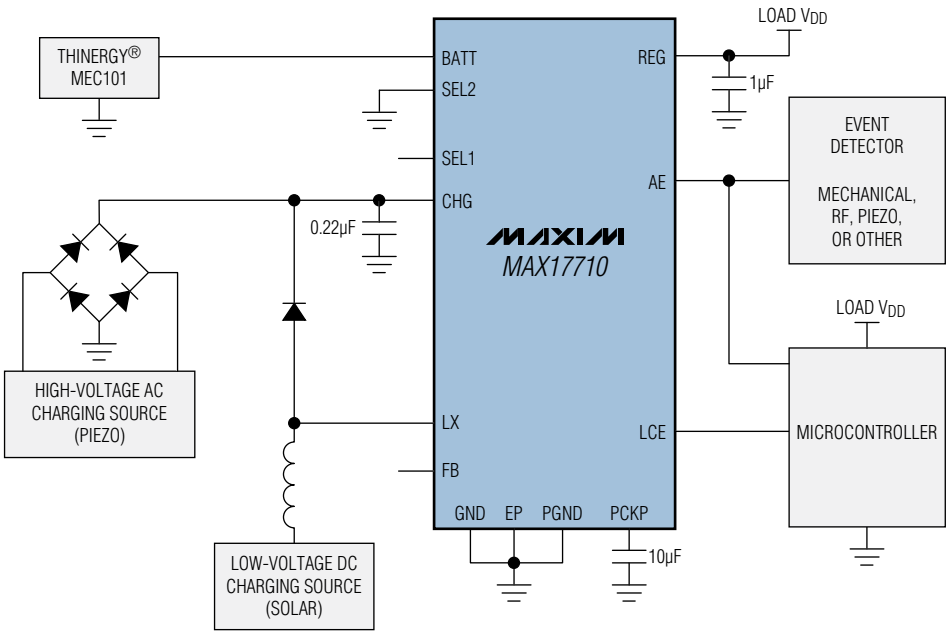
Enable Wireless Links That Need No Battery Replacement

MAX17710

The MAX17710 is an energy-harvesting battery charger/protector. It is designed to capture power from unconventional sources such as light, vibrating piezoelectric elements, thermoelectric modules, radio frequency energy, and magnetic energy. It takes the electrical signals from these unregulated, sometimes low-voltage sources and boosts them as needed to enable charging a battery, supercapacitor, or microenergy cell. While managing the power and protecting the storage device, it provides a regulated output voltage.

Benefits

- Virtually eliminates battery replacement maintenance in wireless modules
  - Harvests energy from unconventional sources
  - Allows incorporation of a rechargeable energy storage device
  - Charges the storage device from lower voltage sources
  - Protects the energy storage device



The MAX17710 energy-harvesting charger and protector is shown harvesting energy from a variety of low-voltage and high-voltage sources while powering a microcontroller with a regulated supply.

Radio Links Ease Installation of Remote Occupancy Sensors

MAX1472, MAX7057, MAX9636/MAX9637/MAX9638, MAX9060–MAX9064

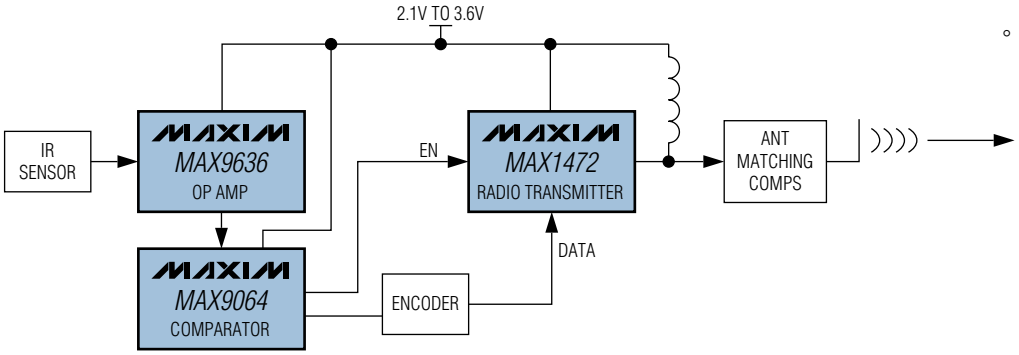
The MAX1472 and MAX7057 ISM-Band radio transmitters, along with the MAX9636/7/8 low-noise op amps and MAX9060–MAX9064 comparators, can be used as critical building blocks in occupancy sensors for building security. The MAX9636/7/8 op amps process the tiny voltages in IR sensors and motion sensors, the MAX9060–MAX9064 comparators complete the alarm circuits, and the MAX1472 and MAX7057 transmitters send the information over a radio link to a keypad or control center.

These devices are well-suited for low battery-current operation, with shutdown currents of a microampere or less. The radio transmitters typically draw 10mA during the short time they are sending information over the air.

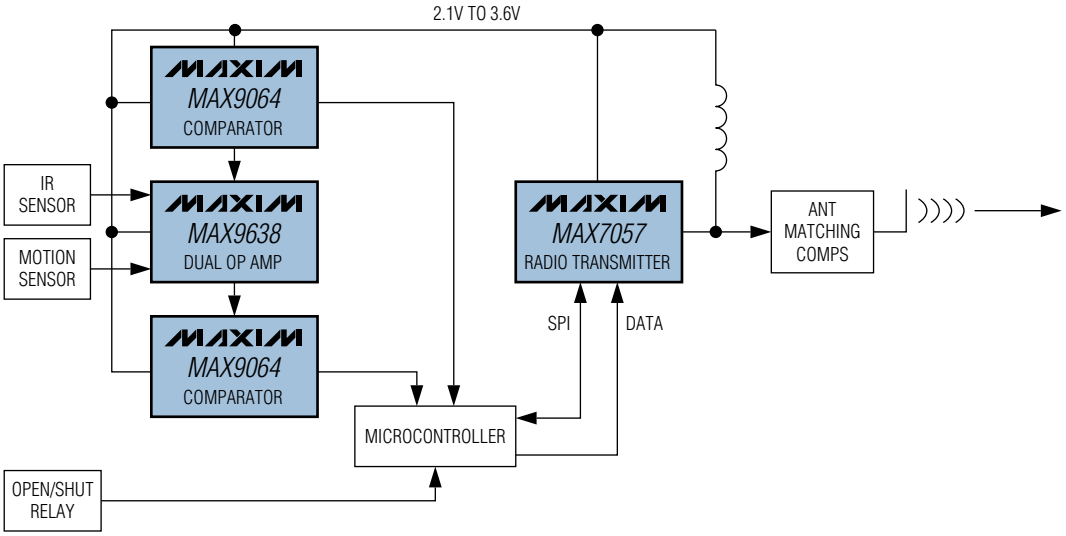
Single and multiple occupancy sensor systems can be supported. The MAX1472 operates at any single frequency in the 300MHz to 450MHz license-free band, determined by an external crystal. The MAX7057 can be directed by a simple microcontroller to operate at multiple frequencies using a single crystal. Adding a microprocessor and multiple sensors can support more than one radio link by changing frequencies.

Benefits

- No need to run wires
  - Radio link sends alarm indication
  - 2.1 to 3.6V operation compatible with most batteries
- Long battery life
  - 100nA operating current for comparators
  - 10nA shutdown current for transmitters
  - 1µA shutdown current for op amps
- High sensitivity to small sensor signals
  - Low bias current and noise density in op amps
- Wide temperature range
  - -40°C to +125°C for transmitters
  - -40°C to +125°C for op amps
  - -40°C to +125°C for comparators
- Simple or multiple sensors
  - IR sensor with simple encoder, one radio frequency
  - IR, motion, relay sensors with microcontroller and multiple radio frequencies



The MAX9636/MAX9064/MAX1472 in a single remote occupancy sensor.



The MAX9638/MAX9064/MAX7057 with multiple remote occupancy sensors.

Recommended Solutions

Thermal Management

Part	Description	Features	Benefits
Temperature Sensors			
DS7505	Thermostat with nonvolatile thresholds	High precision ±0.5°C accuracy from 0°C to +70°C, user-definable, nonvolatile thermostat settings	Provides thermostat function on stand-alone equipment with thresholds saved, even when powered down.
MAX6682	Thermistor-to-digital converter	Converts thermistor temperature to SPI data, 10-bit resolution	Eases design with direct conversion to digital data.
MAX1402	Platinum RTD-to-digital converter	Oversampling ADC with precision current sources to excite RTD, 16-bit, 480sps	Reduces BOM for 4-wire RTD solutions.
MAX31855	Thermocouple-to-digital converter	Converts thermocouple signal to digital SPI-compatible data, temperatures from -270°C to +1800°C	Cold-junction compensation eases design of thermocouple temperature sensor signal conditioners.
Fan Controllers			
MAX31785	6-channel intelligent fan controller	Closed-loop speed control adjusts fan speed to level only needed to minimize noise and power	Simplifies µC overhead by handling fan speed adjustments for multiple fans automatically.

Position Sensors

Part	Description	Features	Benefits
MAX44000	Proximity sensor	On-board IR LED driver, wide operating temperature range, small 2mm x 2mm package	Provides simplified proximity detection solution.
MAX9924–MAX9927	Variable-reluctance sensor interfaces	Differential input, adaptive peak threshold, precision comparator allows small-signal detection	Ease design in noisy environments with differential input that rejects common-mode signals and detects small signals.
MAX9621	Dual, Hall-effect sensor interface	Interface for two Hall-effect sensors provides redundancy for fail-safe operation, protection to 60V	Provides simple to implement fail-safe redundancy solution with built-in sensor protections.

Humidity Sensors

Part	Description	Features	Benefits
DS1923	Humidity and temperature sensor/ data logger	1-Wire humidity and temperature data logger	Provides complete humidity and temperature data logging solution.

Light and Proximity Sensors

Part	Description	Features	Benefits
Ambient Light Sensors			
MAX44009	Ambient light sensor with industry's lowest power	< 1µA operating current. 1.7V to 3.6V supply, 0.045 lux to 188,000 lux range, rejects IR and UV, 22-bit dynamic range	Provides optimal visual display brightness.
Proximity Sensors			
MAX44000	Proximity and ambient light sensor	Integrated IR LED driver and receiver	IR LED pulsing avoids proximity errors from extraneous IR sources.
RGB Sensors			
MAX44006*, MAX44008*	RGB color sensor, IR sensor, temperature sensor	Six sensors in one package provide reliable true-color digitization	Ease design of color temperature measurement systems.

Sensor Signal Amplifiers

Part	Description	Features	Benefits
Op Amps			
MAX9632	Single low-noise op amp for industrial applications	4.5V to 36V operation, 125µV V_{OS}, 0.94nV/√Hz input voltage noise, 55MHz BW, shutdown mode	Provides ultra-low noise amplification to ease detection of very small sensor signals.
MAX44251	Dual op amp with auto zero for ultra-high DC precision in industrial applications	2.7V to 20V operation, 6µV V_{OS}, 5.9nV/√Hz input voltage noise, 5MHz BW	Provides ultra-precision DC amplification to maintain system accuracy.
MAX9636/7/8	Op amp with low input bias current	0.8pA input bias current, low 36µA supply current	Ultra-low input bias current keeps low signal levels valid in smoke detectors and other wireless sensors.
Comparators			
MAX9060–MAX9064	Small, low-power comparator	1mm x 1mm package, ultra-low 100µA operating current, internal reference on some	Ultra-low power enables threshold detection in battery-powered sensors while saving battery life.

*Future product—contact the factory for availability.

Control Panels and Displays

Part	Description	Features	Benefits
Touch-Screen Controllers			
MAX11800, MAX11802	Resistive touch-screen controller with SPI interface	4-wire touch interface with ±8kV ESD on inputs and extended temperature range for high reliability, processes touches to minimize system interrupts	Minimize overhead on system microprocessor.
Switch Debouncers			
MAX16054	Switch debouncer with high ESD protection in single/dual/octal configurations	±25V fault protection, ±15kV ESD protection, -40°C to +125°C	Enhances safety by eliminating false inputs.
LED Drivers			
MAX6979	16-port LED driver with fault detection and watchdog	Constant current drive up to 55mA, 25Mbps 4-wire serial interface, detects open LEDs, blanks display if watchdog timeout	Enhances safety by assuring properly displayed data.
MAX6966, MAX6967	10-port LED driver with PWM intensity control	PWM phase spreading smooths load current, unused ports can be GPIOs	Optimize performance of LED displays with PWM dimming as needed in elevators.
High Brightness LED Drivers			
MAX16814	4-channel high-brightness LED driver	Accepts 4.75V to 40V DC input, switch-mode converter keeps efficiency high, 20mA to 150mA LED string current	Simplifies design of backlighting solutions for control panels and other applications with built-in fault detections and dimming.
MAX16821	High-power synchronous HB LED drivers with rapid current pulsing	Up to 30A output current, on up to 28V DC supply, flexible switching architecture, average current-mode control	Allows rapid LED pulsing for emergency strobe light applications while minimizing component count.

Energy Harvesting

Part	Description	Features	Benefits
Energy-Harvesting Charger			
MAX17710	Energy-harvesting charger and protector	Complete power-management IC boosts input from small energy harvesting transducers and charges battery	Allows wireless systems to use rechargeable batteries to reduce maintenance.
Energy Measurement			
78M6618	Octal energy measurement IC	< 0.5% Wh accuracy over 2000:1 current range, power factor measurement	Simplifies task of accurately measuring energy.
78M6613	Single-phase energy measurement IC	<0.5% Wh accuracy over 2000:1 current range, power factor measurement	Simplifies task of accurately measuring energy.

Power over Ethernet (PoE)

Part	Description	Features	Benefits
Power-Sourcing Equipment			
MAX5980	Quad IEEE 802.3at/af power-sourcing equipment controller for PoE	Up to 70W per port, low-power-loss solution keeps equipment small, while meeting PSE-ICM V2 requirements	Eases thermal design of small high-output power-sourcing equipment for PoE applications.
Powered Device Equipment			
MAX5969D	IEEE 802.3at/af powered device interface controller for PoE	Integrated power MOSFET with inrush current control, provides detection signature and classification signature, 100V rating increases robustness, sleep mode saves power	Eases design of highly efficient and robust Ethernet-powered devices.

Powerline Communications

Part	Description	Features	Benefits
Powerline Communications Interface			
MAX2981	Powerline communication analog front-end transceiver and line driver	HomePlug 1.0-compliant AFE, 50Msps, automotive grade temperature range for use in industrial applications	Enables HomePlug 1.0 equipment to be used in harsh industrial and building automation environments.
MAX2982*	Powerline communication MAC/PHY digital transceiver	Works with MAX2981 to provide a complete solution, 14Mbps data rate, 56-bit DES encryption, 84 carrier OFDM PHY for reliable communication in noisy environments	Enables HomePlug 1.0 equipment to be used in harsh industrial and building automation environments.

Access Control

Part	Description	Features	Benefits
Secure Supervisor			
DS3600	Secure supervisor with 64B nonimprinting memory with tamper detection and response	Nonimprinting memory with high-speed erase upon tamper detection, multiple tamper detections, tamper-event timestamping, meets NIST FIPS 140-2 requirements	Simplifies solution for access control to highly secured facilities.
iButton			
DS1961S	Serial number iButton with SHA-1 authentication	Unique factory-lasered 64-bit registration number provides absolute traceability, durable stainless steel case, SHA-1 authentication prevents cloning	Provides rugged solution for secure access.
RFID Key			
MAX66140	RFID card compliant to ISO 15693 protocol, secure memory card for contactless short range communication	13.56MHz ISO 15693 RF interface, 64-bit unique identifier, 64-bit secret, 1Kb EEPROM, ISO 10118-3 SHA-1 authentication	Minimizes cost of secure access.

*Future product—contact the factory for availability.

Interface

Part	Description	Features	Benefits
RS-485 Transceivers			
MAX13448E	±80V fault-protected full-duplex RS-485 transceiver	Fail-safe against open or shorted inputs, ±8kV ESD protection	Provides a robust interface protected against various fault conditions.

Wireless

Part	Description	Features	Benefits
Transmitters			
MAX7044	ASK transmitter in tiny package	+13dBm transmit power, SOT23 package, 2.1V to 3.6V supply, data rates to 100kbps, 7.7mA power draw at 50% duty cycle, clock output eliminates µC crystal	High-efficiency solution prolongs battery life.
MAX7049	ASK/FSK transmitter operating in 288MHz to 945MHz range	+12dBm Tx power at high bands while circuit drain is low 31.5mA supply current, fractional-N synthesizer gives frequency agility, programmable output power	Provides flexible solution to balance power vs. battery life; eases transmit frequency selection.
MAX7057	ASK/FSK transmitter with programmable transmit frequency	Internal antenna matching components, 2.1V to 3.6V supply, data rates to 100kbps	Enables multiple radio links by changing frequency.
MAX1472	ASK transmitter operating in the 300MHz to 450MHz range	Data rates to 100kbps, 2.1V to 3.6V supply, low 5.3mA operating supply current	Low-power, low-voltage operation provides long battery life in wireless applications.
Receivers			
MAX7036	ASK receiver operating in the 300MHz to 450MHz range	Internal IF filter, high sensitivity to -109dBm, 3.3V to 5V supply range	Reduces BOM due to internal IF filter.
MAX7042	FSK receiver operating in the 308MHz to 433.92MHz range	High sensitivity to -110dBm at 315MHz and -109dBm at 433.92MHz, fast < 250µs startup, low 6.4mA receive current, 20nA standby current	High FSK sensitivity eliminates need for external LNA reducing BOM and extending range.
MAX1471	ASK/FSK receiver operating at 315MHz/434MHz	High sensitivity to -114dBm ASK, -108dBm FSK, integrated 45dB image reject, SPI programmable, polling feature to save power, -40°C to +125°C	Support for simultaneous ASK and FSK reception provides design flexibility.
Transceivers			
MAX7032	ASK/FSK transceiver with fractional-N PLL transmitter	High sensitivity to -114dBm ASK, -110dBm FSK, integrated > 45dB image reject, SPI programmable, low current draw, -40°C to +125°C	High ASK/FSK sensitivity extends range.

Microcontrollers

Part	Description	Features	Benefits
MAXQ610	16-bit microcontroller with infrared module	Ultra-low power 0.2µA stop mode, protection feature locks access to firmware, 1.7V to 3.6V supply	Ultra-low power reduces battery maintenance costs.
MAXQ1004	16-bit microcontroller with AES encryption	High security against tamper, SPI interface, 1-Wire slave interface, 300nA stop mode, 1.7V to 3.6V supply	Provides high data security while using very low power.

Motor Control

Overview

Introduction

Motor control design for industrial applications requires attention to both superior performance and ruggedness. Maxim's feature integration and superior specifications enhance motor controller equipment precision while improving robustness in harsh industrial environments.

Motor controllers either control variable power supplies to the motor or to electronic switches between the power supply and the motor. These switches are precisely timed to open and close to make the motor rotate most effectively. The timing is often governed by complex mathematical equations based on motor architecture and electromagnetic theory. Depending on the application, a motor controller can be as simple as a variable-voltage generator, a pulsed-DC voltage source, or a complex signal generator requiring sophisticated digital signal processing algorithms to generate the correct timing. For large motors, those in the multihorsepower range with multiple power phases, precise control is essential. At a minimum, the wrong timing can result in extreme power use. In the worst case, wrong timing can destroy the motor and the installation itself.

Many electric motors have maximum torque at zero RPM, so these large motors must be soft-started. To reduce maintenance to a minimum, the mechanical mechanisms (clutches) that traditionally provided this soft-start capability are rapidly being replaced by electronic soft-starters or variable frequency drives (VFDs). In some applications motors must supply both forward and reverse tension to the load; optimally, braking energy from overhauling loads is fed back into the AC line using regenerative VFDs instead of being wasted as heat in large braking resistors or in high-maintenance mechanical brakes.

Motor control is a very significant portion of the Control and Automation market. According to U.S. Department of Energy, motor driven equipment accounts for 64% of the electricity consumed by U.S. industries. Furthermore, electric motors consume about 45% of the world's electricity according to the International Energy Agency (IEA) report of May 2011 on global energy consumption by electric motor driven systems. By comparison, lighting is a distant second consuming 19%. With the cost of energy rising steadily, plant operators look for ways to reduce energy consumption while maintaining throughput. Furthermore, with the availability of reasonably priced and highly capable motor controllers for all types of motors, plant engineers are free to choose motor types that are less expensive, more efficient, and require less maintenance.

To put the energy savings opportunity in perspective, compare motor power consumption vs. speed when driving fans and centrifugal pumps. The torque needed rises with speed, resulting in power draw that is proportional to the *cube* of the speed! In other words, reducing the speed to one-half of full speed drops the power to one-eighth of full power. Even dropping the speed to 75% of full speed drops the power consumption to 42% of full power (0.75 cubed = 0.42). It is clear that *significant* savings in energy use can be realized by even small reductions in speed. This fact, in turn, justifies the use of VFDs in applications that can tolerate the speed reduction. Of course, speed reduction equates to performing the work more slowly, which, in some cases, directly impacts throughput. Nonetheless, there are numerous applications where motors do not need to run at full speed to accomplish the work quickly enough. Pumping out a tank of fluid may not need to be done as fast as possible. Venting a room may need a full-speed fan at first, but once the air is moving a slower speed may suffice. The EIA report (May 2011) states that it is feasible and cost effective to save 20% to 30% of total motor power consumption worldwide.

Certainly adding variable-speed controllers adds cost to the installation; however, the forecasted energy savings will soon offset those initial expenses. The return-on-investment calculations are often straightforward.

Interfacing to the Motor Controller

A very important aspect of every motor controller in the industrial control and automation setting is the communications interface between the factory control system and the individual motor controller. All the block diagrams in the individual motor controller sections show a control panel that provides a direct user interface at the controller and a standard separately wired communications interface that connects to the fieldbus. The fieldbus ultimately runs back to a PLC (programmable logic controller) that sends commands to the motor controller such as motor start, motor acceleration, speed adjustment, motor stop, etc. An additional option exists: powerline communications (PLC, not to be confused with programmable logic controller). This technology gives the option of sharing command and control connections with power connections between the PLC (programmable logic controller) and the motor controller.

Motor Types

Brushed DC Motors (BDCs)

Brushed DC (BDC) motors are among the first motor types put to practical use and they are still popular where low initial cost is required. These motors have a wound rotor armature and either a permanent magnet stator or field wound stator. Brushes slide across the segments of the commutator on the rotor to switch the DC power source to the appropriate windings on the rotor.

BDC motors have their place for two important reasons: low initial cost and ruggedness, because no electronics are needed inside the motor. Because the motors suffer from wear of the brushes, brush springs, and commutators, they require high maintenance in intensive-use applications. Sparking also occurs between the brushes and the commutator

as a part of normal motor operation. This, in turn, creates EMI/RFI and small amounts of ozone. Where system cost is a priority, BDC motors are a low-cost solution. While their efficiency is generally lower than brushless DC (BLDC) motors, they approach equality under high-load conditions.

Controllers for BDC Motors

The only variable available to control the speed of a BDC motor is the supply voltage. The voltage can be varied or a fixed voltage can be pulsed with variable duty cycle. For high efficiency in a variable voltage approach, a switch-mode power supply is required. Most designers are abandoning linear voltage regulation because of its inherently low efficiency. One way to realize a variable-voltage power supply from any switch-mode voltage regulator is to inject or extract current into or out of its feedback node using a current sink/source DAC. See **Figure 1**. When the

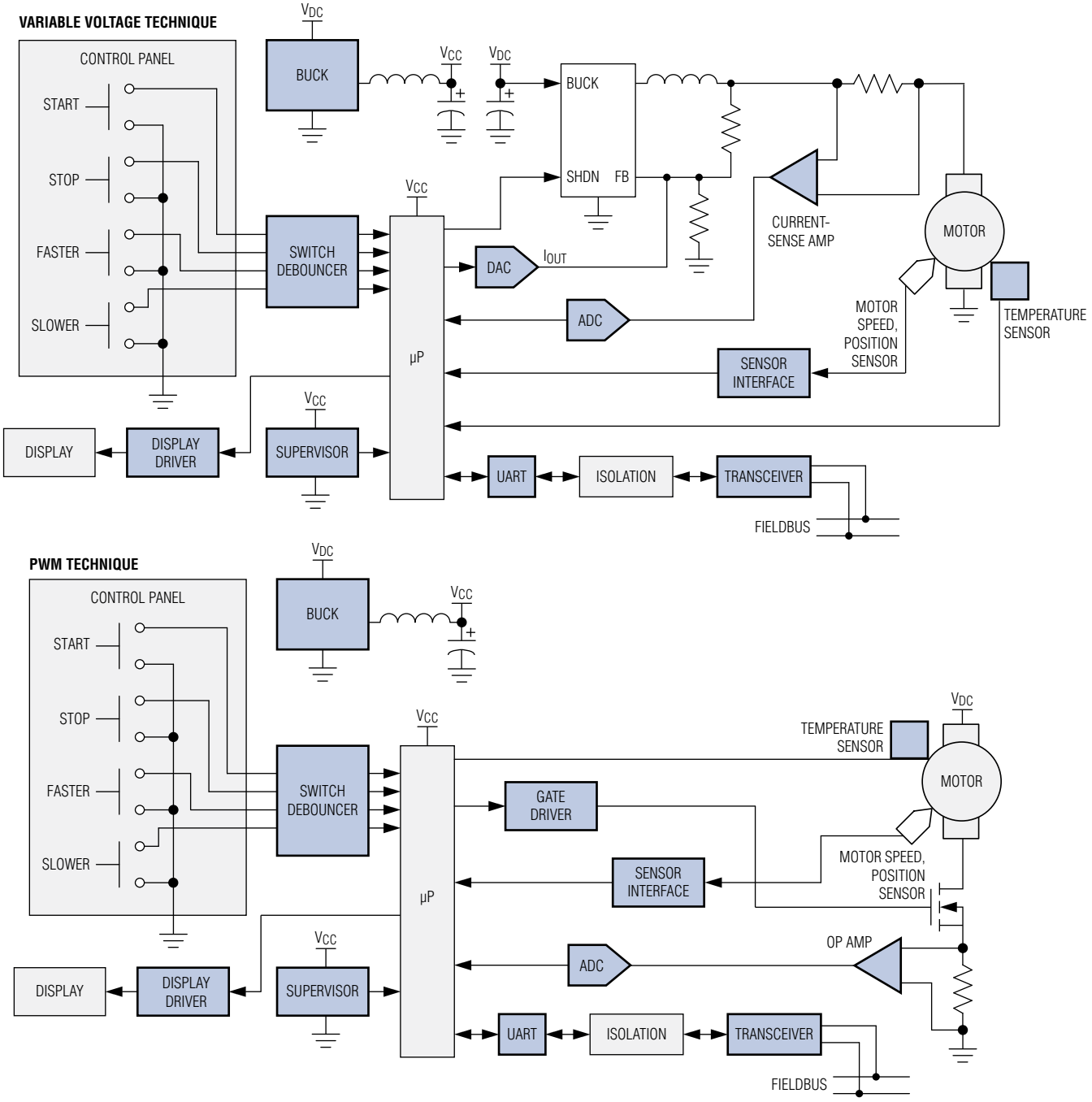


Figure 1. Two control techniques for BDC motors. The upper diagram shows a variable voltage technique that is high efficiency due to the switching power supply. The lower diagram shows the PWM technique that can be lower cost if the motor is rated for the full supply voltage.

user adjusts the speed control or when the microcontroller receives a command through the electronic interface, the microcontroller then instructs the current sink/source DAC (e.g., DS4432) to change its output current value. This forces the regulator to change the output voltage to the motor up or down, respectively, to keep the feedback pin's voltage constant.

Alternatively, if the motor can handle the high-DC voltage, one can convert the input control to a pulse-width-modulated (PWM) duty cycle applied to a power switch between the power supply and the motor. By varying the duty cycle, the average power to the motor is adjusted, as is its output power and speed. If constant speed is needed under a varying load, then motor speed detection is needed. This motor speed signal (usually a pulse frequency proportional to the motor rotation rate) must be fed into a controller that will respond by either adjusting the motor voltage or the PWM duty cycle. With sufficient switching frequency, the inductance of the motor windings act as a lowpass filter that keeps the motor current close to constant with only minor ripple, thus producing low torque ripple.

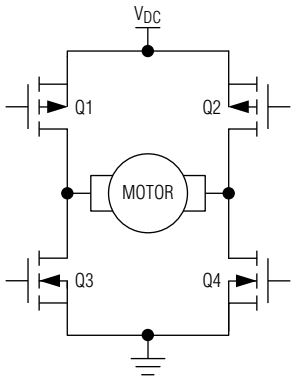


Figure 2. H-bridge for driving a BDC motor in both directions. When Q1 and Q4 are on, the motor moves one direction. When Q2 and Q3 are on, the motor moves in the opposite direction.

To reverse the direction of the BDC motor, current must flow through the motor in the opposite direction. This can be accomplished using power MOSFETs or IGBTs in an H-bridge configuration (**Figure 2**). These MOSFETs can be either voltage controlled or PWM controlled for speed control.

Brushless DC (BLDC) Motors

A BLDC motor spins the magnets instead of the windings—the inverse of a BDC motor. This has advantages and disadvantages. A BLDC motor has neither commutator nor brushes, so it requires less maintenance than a BDC motor. The BLDC motor's rotor can take different forms, but all are permanent magnets.

The armature is fixed and holds the stator windings; the rotor carries the magnets and can either be an "inrunner" or an "outrunner." Inrunners have the rotor inside the stator and outrunners have the rotor outside the stator (**Figure 3**). Either approach eliminates the problem of connecting the power source to a rotating part through a commutator. The brushes and mechanical commutator are replaced by electronic commutation of the stator windings. This increases motor life significantly. The initial cost of a BLDC motor is higher than an equivalent BDC motor, although the cost of permanent magnets has decreased significantly over the past years. With precise commutation and rotor position sensing, efficiency is generally higher than equivalent BDC motors. They also produce more torque per unit weight. Another significant advantage for industrial applications is that since there are no brushes, there are no sparks generated, so the BLDC motors can be used in explosive environments.

Due to their higher efficiency over a wide range of speeds and loads, BLDC motors are seeing wider use in heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems.

Figure 3. Disassembled outrunner BLDC motor. Fixed armature carries the stator windings. The rotor carries the permanent magnets.

Controllers for BLDC Motors

Since the commutation in a BLDC motor (**Figure 4**) is electronic, some means is required for detecting rotor position relative to the stationary armature. Typical solutions for this are Hall-effect sensors and rotary encoders such as optical encoders, resolvers, or rotary variable differential transformers (RVDTs). More designs are using sensorless approaches where stator coil back EMF variation is sensed, which indicates rotor position. This information is typically sent to a microprocessor to determine power FET drive timing. Various user interfaces allow soft-starting, acceleration control, speed control, and response to locked rotor.

Stepper Motors

Stepper motors are really more like rotary positioners than motors. They are usually smaller motors with many poles used for precise positioning applications (**Figure 5**). They are often driven "open loop," meaning there is no position detection. Their position is assumed to follow the step commands exactly. Loss of step position can occur, however, so some mechanism must be provided to indicate slippage and to reset proper positioning. At low drive rates, they come to a complete stop between each step. Many drive waveforms are possible, the simplest has each winding energized one at a time. Other variations are possible where overlap in energization occurs between adjacent windings to provide smaller steps. Microstepping is achieved with sinusoidal, overlapping current waveforms that give very smooth and quiet rotation.

Figure 5. Stepper motor (windings removed) showing multi-toothed rotor and stator design for fine stepping.

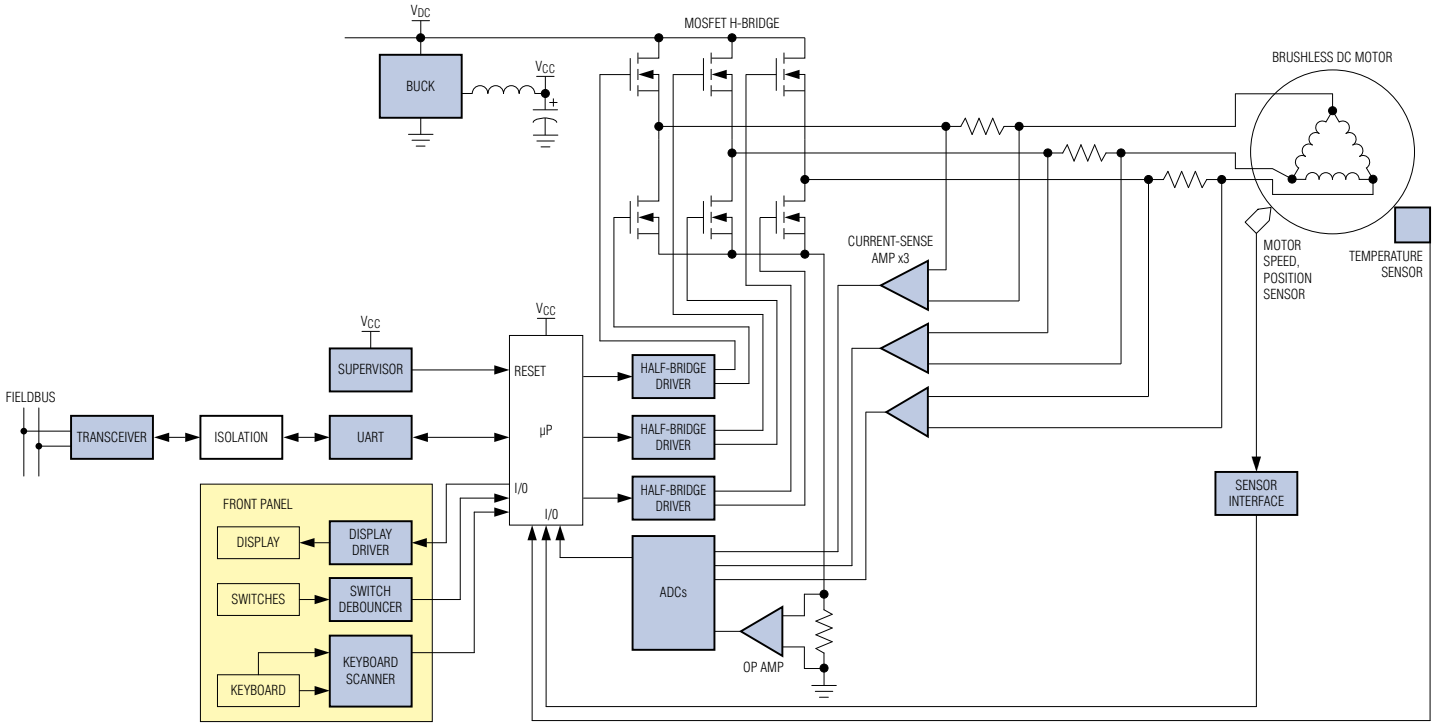


Figure 4. Controller for BLDC motor.

Controllers for Stepper Motors

Stepper motors are constant power motors if driven with a constant supply voltage. As speed increases, torque decreases. This happens because of the limitation on current ramp rates in the windings due to their inductance. Maximum torque is realized at zero speed. So to increase torque at higher speeds, high-voltage drivers with current limiting are sometimes used (**Figure 6**). These are called "chopper drives," and are designed to generate a nearly constant current in each winding rather than simply switching a constant voltage. On each step, a very high voltage is applied to the winding. When the current limit is reached, the voltage is turned off or "chopped." At this point the winding current starts ramping down to a lower limit where the voltage is again turned on, keeping the winding current relatively constant for a particular step position. The additional electronics to sense winding currents and to control the switching adds some cost and complexity, but it allows stepper motors to be driven with high torque at high speed.

Microprocessors are commonly incorporated in stepper motor drivers to provide the controls needed. Sophisticated control capability is common for stepper motors since they are often employed in machines that require fast precision movements, such as in robotics. Acceleration/deceleration profiles, holding torque, and other parameters are often provided for.

Switched Reluctance Motors (SRMs)

Switched reluctance motors (SRMs) are a form of stepper motor, but are usually much larger and have fewer poles than the traditional stepper motor. The key to these motors is that the rotor is made of only ferromagnetic material and has no windings. It is a very reliable, low-maintenance motor with high power density at low cost, all of which come at the expense of more complex electronic controls.

Opposing stator poles are energized in sequence and the rotor poles closest to the energized stator poles become magnetized and are attracted to them, reducing magnetic reluctance when brought into alignment. Before full alignment is achieved, the next phase is energized to keep the motor turning. There is no need for any transfer of electrical power to the rotor so there are no brushes, commutators, or slip rings. With electrical commutation there are no sparks so these motors can be used in explosive environments. They are also good for holding a load in a stationary position for long periods of time.

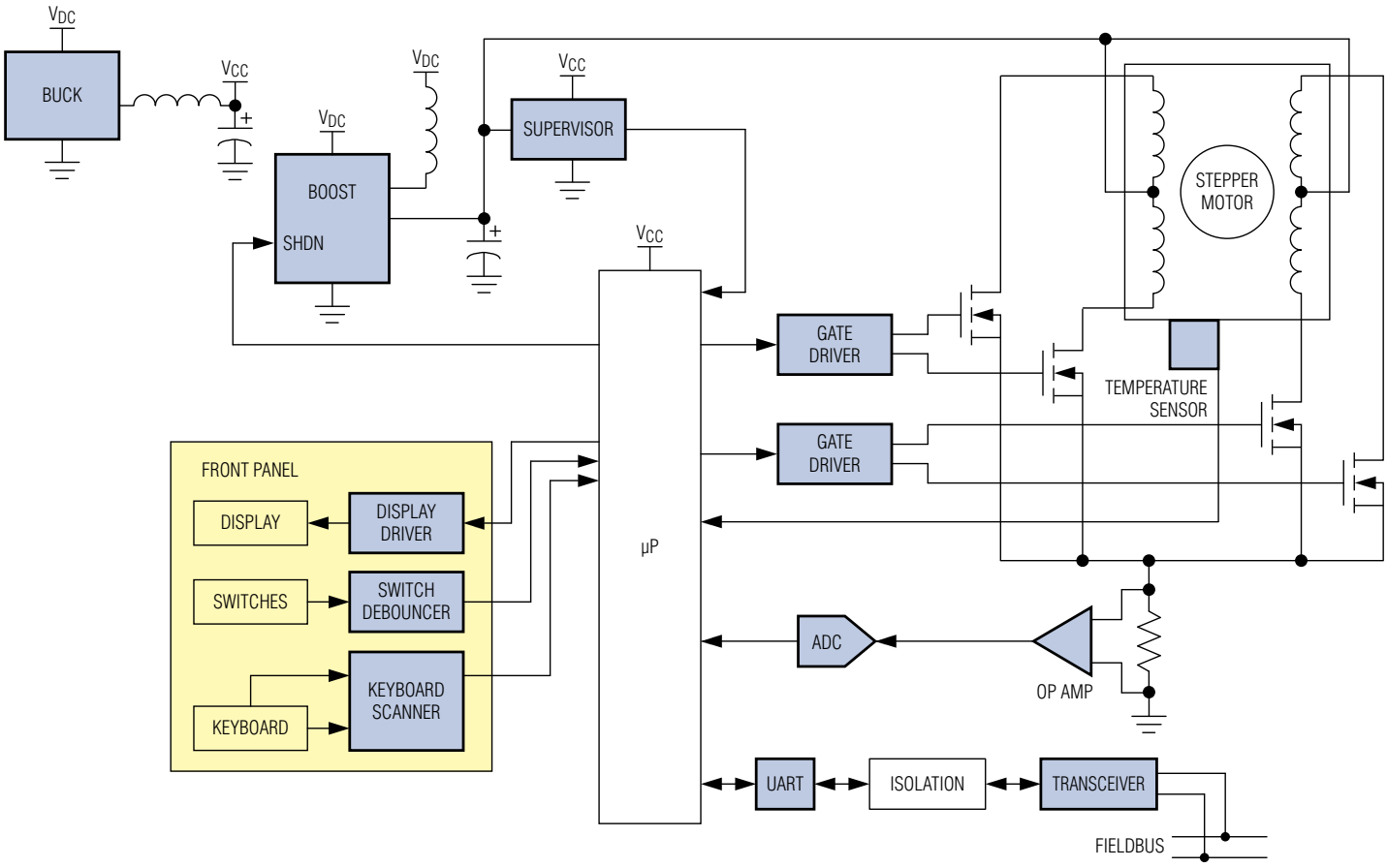


Figure 6. Controller for stepper motor. The boost regulator and the current sense per phase allow current to ramp quickly in each pole of the motor. Motor response is fast. When the maximum current per phase is reached, the boost regulator is shut down until the minimum current per phase is reached again. The cycle is repeated until the next step is made.

Controllers for SRMs

SRMs are similar to stepper motors because they need power switched to the proper windings at the appropriate times. The most common configuration is similar to an H-bridge, but differs somewhat. The driver is called an N+1 switch and diode asymmetric bridge converter (**Figure 7**). It allows each phase of a 3-phase motor to be energized by the top FET and the appropriate bottom FET, which are both turned on simultaneously (**Figure 8**). The current is allowed to ramp up to a limit, at which point the top FET is turned off. This is the freewheeling mode, where the winding inductance keeps the current relatively constant, ramping down only very slowly with the bottom diode closing the loop around the winding. Then to discharge the phase quickly in preparation for the next step, the bottom FET is also turned off. The voltage across the winding is now clamped to the opposite polarity by the top and bottom diodes. This causes the current to ramp down at about the same rate that it ramped up, except for the effect of two additional diode drops making it ramp down slightly faster. This configuration allows each phase to be switched on and off quickly, especially with a high-voltage supply, allowing for high-speed motor operation at high torque. Figure 8 shows only a single current-sense amp sensing the current on the high-side FET. This is only adequate for simple control systems. Complete control also requires current sensing on each low-side FET.

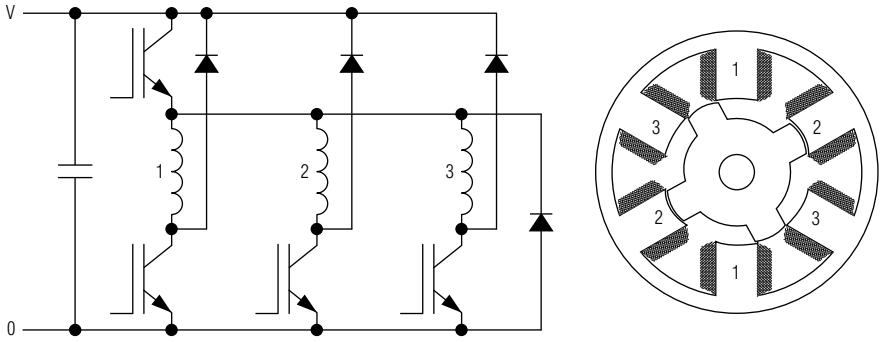


Figure 7. "N+1 switch and diode" asymmetric bridge for driving SRMs. The control circuitry needed for the IGBTs shown is shown in Figure 8.

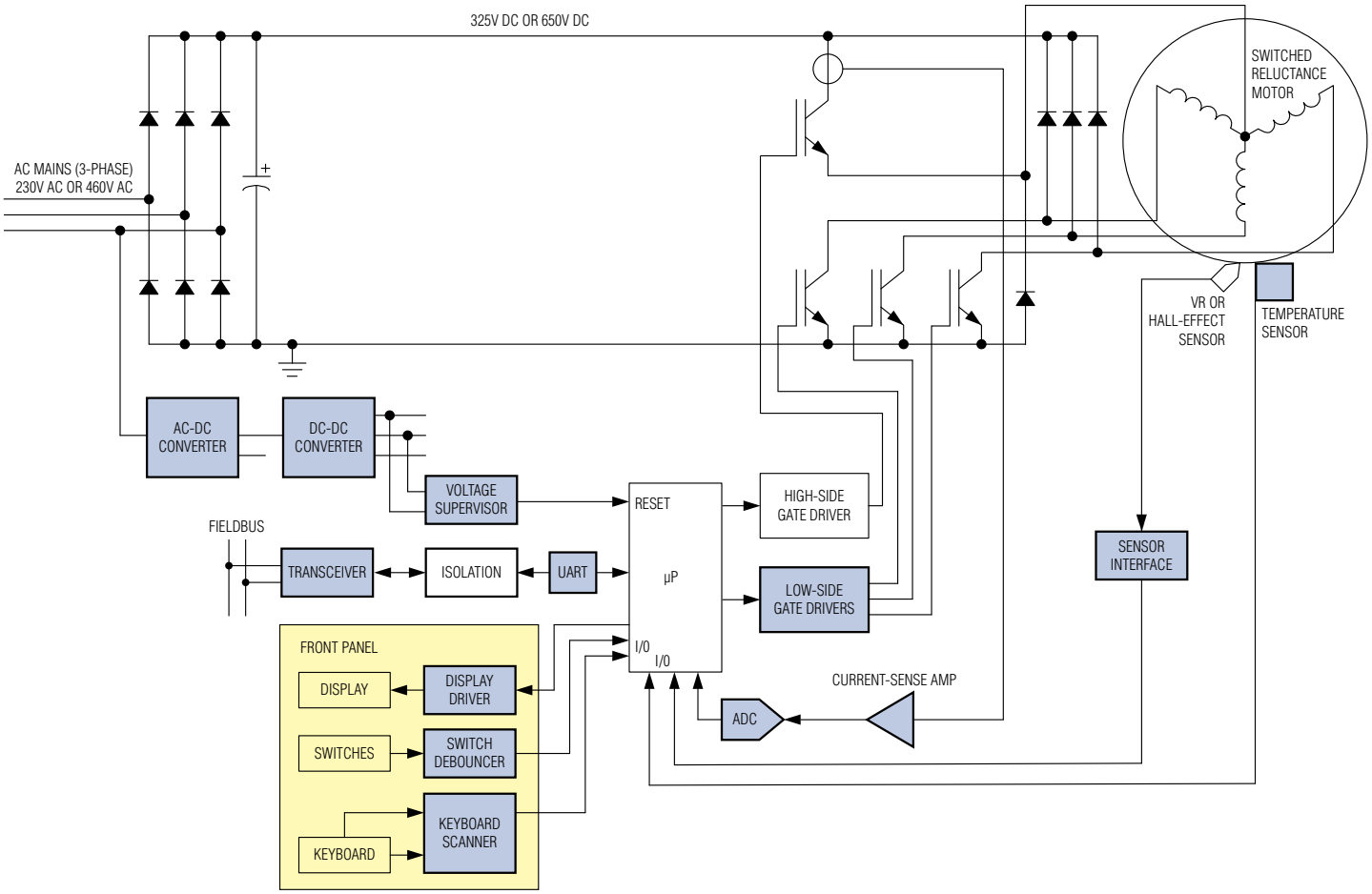


Figure 8. Controller for a switched reluctance motor.

AC Induction Motor

The AC induction motor (**Figure 9**) is the workhorse motor for many industrial applications such as those for driving pumps, blowers, conveyors, cranes, etc. It is one of the simplest and most reliable motor designs and can range in size from a few watts to many kilowatts. The induction motor is an asynchronous motor and is basically an AC transformer with a rotating shorted secondary. The primary winding (stator) is connected to the power source and the secondary winding (rotor) carries the induced secondary current creating a magnetic field. Torque is produced as the rotor field tries to align itself with the applied rotating stator field. No slip rings or commutators are needed since no source power is physically connected to the rotor. The most common designs have three stator windings and are driven from 3-phase AC sources. Although direct connection to AC mains is therefore possible, in most applications, induction motors require some form of soft-starter or VFD.

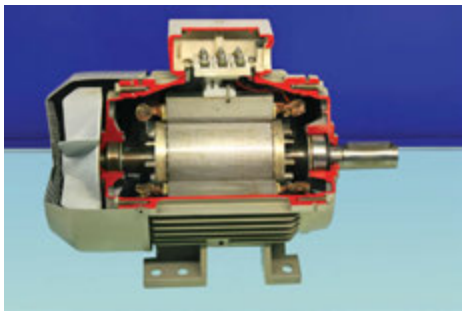


Figure 9. An AC induction motor.

Induction motors "slip" under load. The amount of slip is directly proportional to the torque required to drive the load. Under no-load conditions, no torque is produced and the rotational speed is almost exactly the driving frequency divided by the number of poles in the stator. These motors are easily speed and torque controlled by varying the drive frequency and voltage, respectively. If constant speed is needed, VFDs can use position- or speed-detection feedback to increase the drive frequency as needed to keep the motor speed constant under varying loads.

Controllers for AC Induction Motors

AC induction motors operate with the least torque ripple when the phase current is sinusoidal. Due to the inductance of the windings, the phase can be PWM driven from a fixed DC supply to achieve this current waveform. The two most common approaches to induction motor drive include "vector control" and "direct torque control." These techniques are beyond the scope of this document, but information is readily available. Suffice it to say that to fully implement these control techniques, a fairly powerful processor or DSP is required, but the benefits are many. The result is a VFD (**Figure 10**)

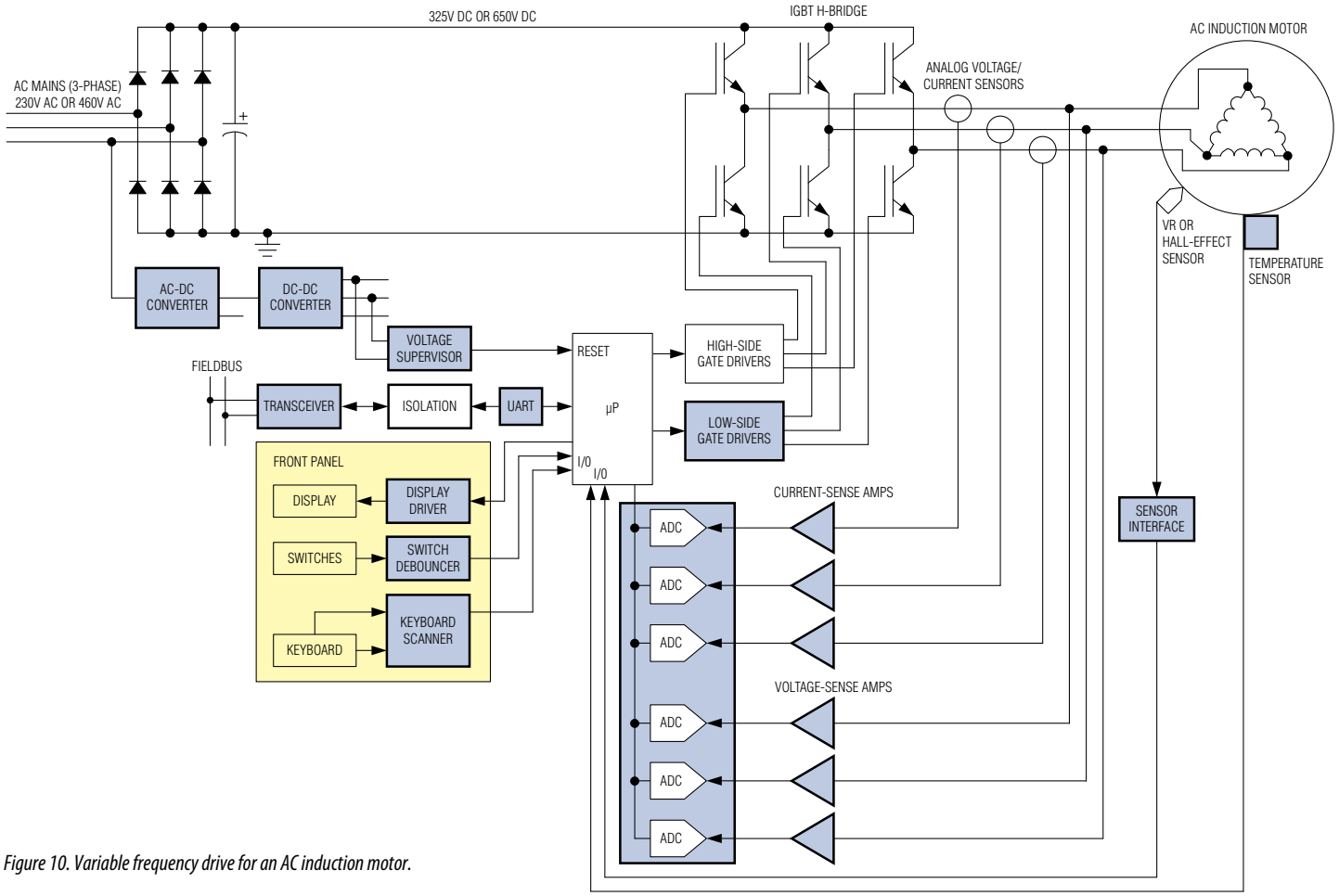


Figure 10. Variable frequency drive for an AC induction motor.

that provides complete control capability over motor soft-starting, acceleration, torque, speed maintenance, deceleration, and holding torque.

Synchronous Motors

A synchronous motor runs synchronously with the AC excitation it receives. Various configurations are possible. One approach applies the AC line to the stator windings around the frame while a DC excitation is applied through slip rings to the rotor. In many synchronous motors the rotor has permanent magnets instead of DC-excited windings. High-speed synchronous motors are used in machining applications where the cutter speed must be maintained at precisely fixed rates or the machined-surface finish will show signs of speed variation.

When driven mechanically, synchronous motors will produce electricity, becoming alternators. They are used extensively in power plants to generate grid power.

DC-excited synchronous motors can also be used in power plants and large factories to correct the power factor by being run under no load in parallel with the large loads. As the DC excitation of the rotor is modified, it produces either a leading or lagging power factor to cancel the nonunity power factor of the load. In this application they are called synchronous condensers.

Controllers for AC Synchronous Motors

Various control methods exist for AC synchronous motors. The motors' stator windings can be driven with variable-frequency AC signals from a VFD, thereby providing soft-starting and exacting speed control. If a low frequency is not first applied to a stopped synchronous motor, it will not self-start. It must be given a chance to "pull in" to synchronization. Some synchronous motors allow the rotor windings to be shorted, temporarily converting it to an induction motor while it starts. Then once it is close to synchronous speed, the short is opened and it becomes synchronous.

Figure 11. Maglev train driven by a linear motor.

If the rotor uses DC excitation, its voltage can vary with a high-efficiency switching power supply and voltage control.

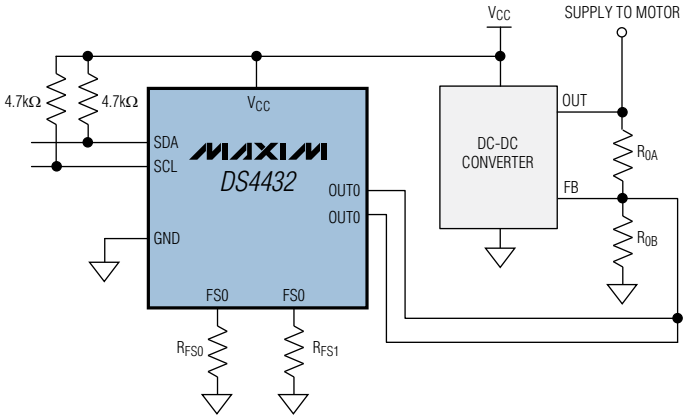
Linear Motors

Linear motors are effectively motors that have been unrolled and laid out flat. The moving part is usually called the forcer and is connected to the external power source while the rails are lined with permanent magnets. The opposite configuration is also used. Everything from maglev trains (**Figure 11**) to rail guns are based on this principle. Very precise machine positioning systems use these motors for cutting large objects with high accuracy. Linear motors include linear induction motors (LIMs) and linear synchronous motors (LSMs). Controllers for linear motors are quite varied due to the wide range of applications for them. Nonetheless, they share similarities with VFDs.

Sink/Source Current DAC Adjusts Power-Supply Output Voltage to Vary Supply to Motors

DS4432

The DS4432 contains two I²C programmable current DACs that are each capable of sinking and sourcing current up to 200µA. Each DAC output has 127 sink and 127 source settings that are programmable using the I²C interface. The current DAC outputs power up in a high-impedance state. Full-scale range for each DAC is set by external resistors providing highly scalable outputs. Fine and course granularity can be achieved by combining the two outputs when set for different ranges.



Typical operating circuit of the DS4432.

Benefits

- Simplicity of DC motor speed control via digital interface
- Easy design reuse due to highly scalable outputs
- Dual outputs with individual range settings provide course and fine motor speed control

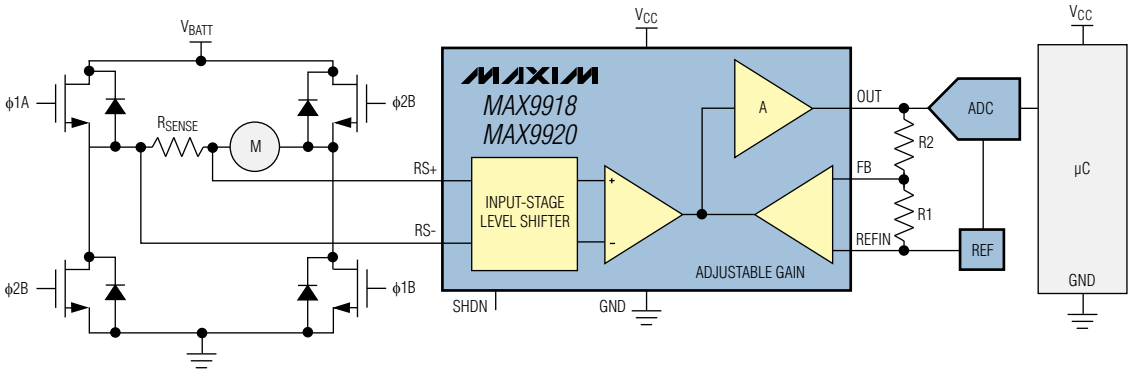
Precise Current Measurements Ensure Better Motor Control

MAX9918/MAX9919/MAX9920

The MAX9918/MAX9919/MAX9920 are current-sense amplifiers with a -20V to +75V input range. The devices provide unidirectional/bidirectional current sensing in very harsh environments where the input common-mode range can become negative. Uni/bidirectional current sensing measures charge and discharge current in a system. The single-supply operation shortens the design time and reduces the cost of the overall system.

Benefits

- Provide reliable operation in harsh motor control environments
  - 400µV (max) input offset voltage (V_{OS})
  - -20V to +75V common-mode voltage range provides reliability for measuring the current of inductive loads
  - -40°C to +125°C automotive temperature range
- Integrated functionality reduces system cost and shortens design cycle
  - Uni/bidirectional current sensing
  - Single-supply operation (4.5V to 5.5V) eliminates the need for a second supply
  - 400µV (max) input offset voltage (V_{OS})
  - 0.6% (max) gain accuracy error



The MAX9918/MAX9920 current-sense amplifiers provide precise uni/bidirectional current sensing in very harsh environments.

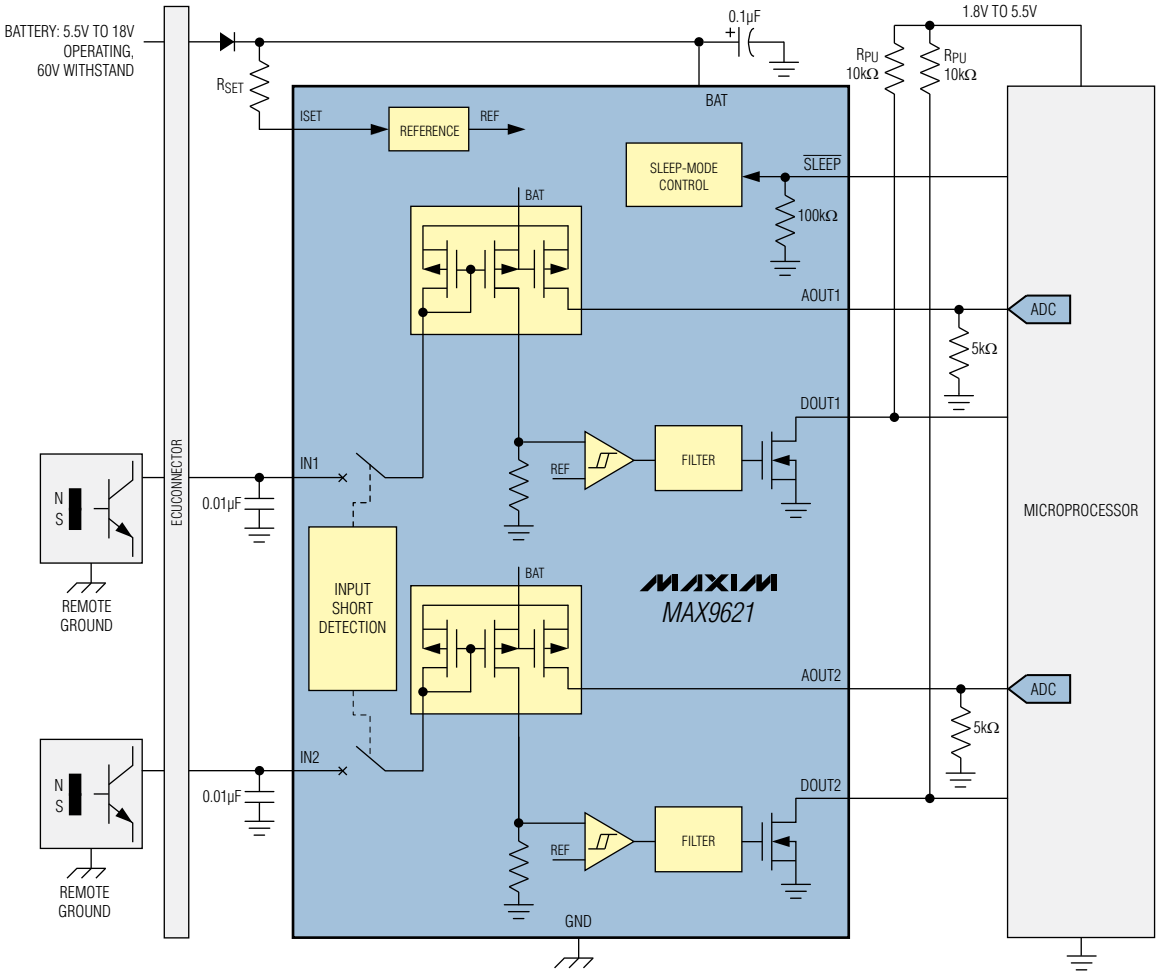
Highly Accurate, Reliable Monitoring of Motor Speed and Position with a Sensor Interface

MAX9621

The MAX9621 is a dual, 2-wire Hall-effect sensor interface with analog and digital outputs. This device enables a microprocessor to monitor the status of two Hall-effect sensors, either through the analog output by mirroring the sensor current for linear information, or through the filtered digital output. The input current threshold can be adjusted to the magnetic field. The MAX9621 provides a supply current to two 2-wire Hall-effect sensors and operates in the 5.5V to 18V voltage range. The high-side current-sense architecture eliminates the need for a ground-return wire without introducing ground shift. This feature saves 50% of the wiring cost.

Benefits

- Integrated functionality eases motor control design, reduces system cost
  - Select the analog or digital output to monitor the Hall-effect sensor's condition
  - High-side current-sense architecture eliminates the need for a ground-return wire and saves 50% of the wiring cost
- Reliable operation in a harsh environment
  - Protects against up to 60V supply voltage transients
  - Detects a short-to-ground fault condition to protect the system

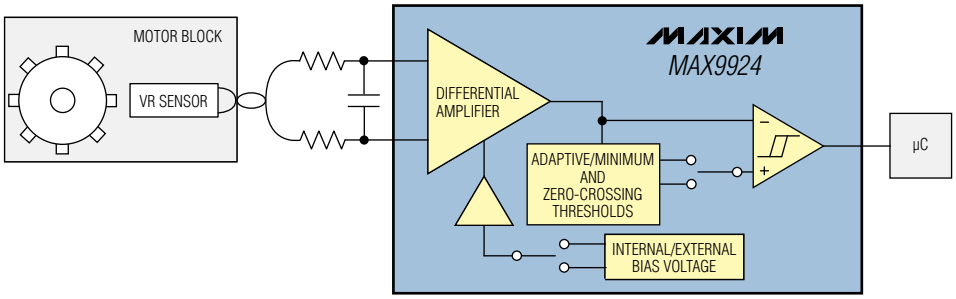


Functional diagram of the MAX9621 Hall-effect sensor interface.

Improve Performance and Reliability in Motor Applications with a Differential VR Sensor Interface

MAX9924–MAX9927

The MAX9924–MAX9927 VR, or magnetic coil, sensor interface devices are ideal for sensing the position and speed of motor shafts, camshafts, transmission shafts, and other rotating wheel shafts. These devices integrate a precision amplifier and comparator with selectable adaptive peak threshold and zero-crossing circuit blocks that generate robust output pulses, even in the presence of substantial system noise or extremely weak VR signals. The MAX9924–MAX9927 interface to both single-ended and differential-ended VR sensors.



Simplified block diagram of the MAX9924 VR sensor interface to a motor.

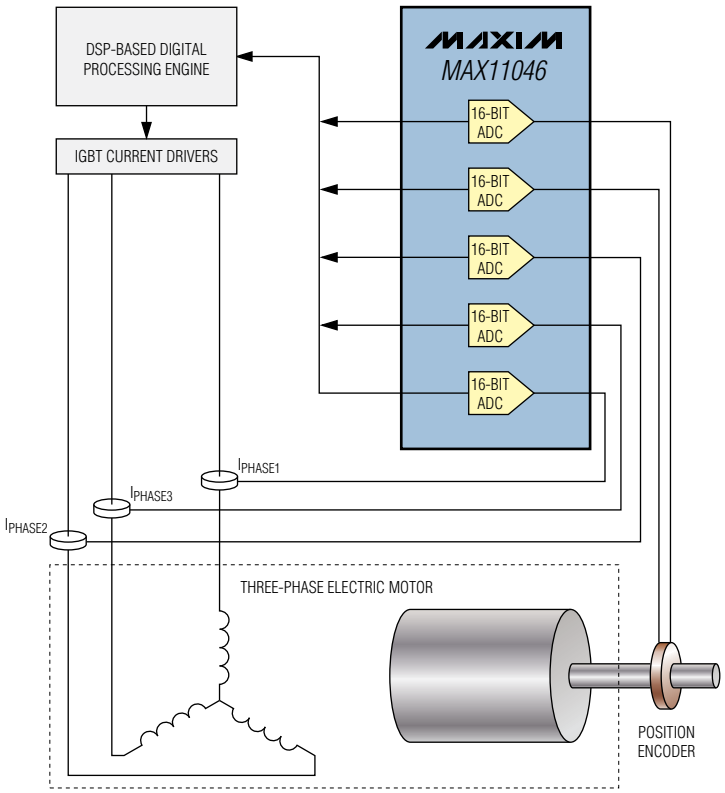
Benefits

- High integration provides accurate phase information for precise sensing of rotor position
  - Differential input stage provides enhanced noise immunity
  - Precision amplifier and comparator allow small-signal detection
  - Zero-crossing detection provides accurate phase information

Resolve Very Fine Motor Adjustments and Operate Higher Accuracy Systems with Simultaneous-Sampling ADCs

MAX11044/MAX11045/MAX11046
MAX11047/MAX11048/MAX11049

The MAX11044–MAX11049 ADCs are an ideal fit for motor control applications that require a wide dynamic range. With a 93dB signal-to-noise ratio (SNR), these ADCs detect very fine changes to motor currents and voltages, which enables a more precise reading of motor performance over time. The MAX11044/MAX11045/MAX11046 simultaneously sample four, six, or eight analog inputs, respectively. All ADCs operate from a single 5V supply. The MAX11044–MAX11046 ADCs measure ±5V analog inputs, and the MAX11047–MAX11049 measure 0 to 5V. These ADCs also include analog input clamps that eliminate an external buffer on each channel.



The MAX11046 ADC simultaneously samples up to 8 analog-input channels.

Benefits

- Industry-leading dynamic range allows early detection of error signals
  - 93dB SNR and -105dB THD
- Simultaneous sampling eliminates phase-adjust firmware requirements
  - 8-, 6-, or 4-channel ADC options
  - Lower system cost by as much as 15% over competing simultaneous-sampling ADCs
  - High-impedance input saves costly precision op amp
  - Bipolar input eliminates level shifter
  - Single 5V voltage supply
  - 20mA surge protection
- Eliminate external protection components, saving space and cost
  - Integrated analog-input clamps and small 8mm x 8mm TQFN package provide the highest density per channel

Recommended Solutions

Part	Description	Features	Benefits
AC-DC and DC-DC Converters and Controllers			
MAX17499/500	Isolated/nonisolated current-mode PWM controllers ideal for flyback/forward topologies	85V AC to 265V AC universal offline input voltage range (MAX17500), 9.5V DC to 24V DC input voltage range (MAX17499), programmable switching frequency up to 625kHz, 1.5% reference accuracy	Primary-side regulation eliminates optocouplers, allowing low-cost isolated supplies.
MAX5069	Isolated/nonisolated current mode PWM controller with dual FET drivers ideal for push-pull and half/full-bridge power supplies	85V AC to 265V AC universal offline input voltage range (MAX5069A/B), 10.8V DC to 24V DC input voltage range (MAX5069C/D), programmable switching frequency up to 2.5MHz, programmable UVLO and UVLO hysteresis	Minimizes footprint due to wide range programmable switching frequency; programmable UVLO/hysteresis ensures proper operation during brownout conditions.
MAX15062*	High-voltage synchronous, micro buck regulator	4V to 36V input voltage range, fixed 700kHz switching frequency, integrated high-side and low-side FETs, internal compensation	Reduces total solution size and cost with high integration and small package.
ADCs			
MAX11044/45/46 MAX11047/48/49	16-bit, 4-/6-/8-channel, simultaneous-sampling SAR ADCs	93dB SNR: -105dB THD; 0 to 5V or ±5V inputs; parallel interface outputs, all eight data results in 250ksps; high-input impedance (> 1MΩ)	High-impedance input saves the cost and space of external amplifier.
MAX1377/MAX1379/MAX1383	12-bit, dual, 1.25Msps, simultaneous-sampling SAR ADCs	0 to 5V, 0 to 10V, or ±10V inputs: 70dB SNR; SPI interface	Serial interface saves cost and space on digital isolators.
MAX11040K	24-bit, 4-channel, simultaneous-sampling, sigma-delta ADC	117dB SNR, 64ksps, internal reference, SPI interface, 38-pin TSSOP package	Reduces motor control firmware complexity.
MAX11203	16-bit single-channel, ultra-low-power, delta-sigma ADC	Programmable gain, GPIO, high resolution per unit power ratio	Eases achieving high-efficiency designs.
DACs			
DS4432	Dual sink/source current DAC with sink and source settings programmable via I^2C interface; range settable with resistors	50µA to 200µA sink/source range, 127 sink, 127 source settings	Provides simple and precise digital speed control for a wide range of DC motor control applications.
Current-Sense Amplifiers			
MAX34406	Quad current-sense amplifier with overcurrent threshold comparators	Unidirectional current sensing; fixed gains of 25, 50, 100, and 200V/V; ±0.6% gain error; 2V to 28V common-mode range	Wide dynamic range supports wide range of motor current-sensing applications.
MAX9918/19/20	-20V to +75V input range; uni/bidirectional current-sense amplifiers	0.6% max gain error, 120kHz -3dB BW, -40°C to +125°C operating temperature range	Wide dynamic range and high accuracy supports wide range of motor current-sensing applications.
MAX9643	High-speed current-sense amplifier	15MHz bandwidth, -1.5V to +60V input range, 50µV max V_{OS}, -40°C to +125°C operating temperature range	Provides very fast response to quickly changing currents in motor control applications.

(Continued on following page)

*Future product—contact the factory for availability.

Part	Description	Features	Benefits
Operational Amplifiers			
MAX9617/18/19/20	High efficiency, zero drift, op amps with low noise and RRIO	10µV (max) V_{OS} over time and temperature range of -40°C to +125°C, 59µA supply current, 1.5MHz GBW, SC70 package	Allow sensing low-side motor current with high accuracy at low power consumption.
MAX9943/44	38V precision, single and dual op amps	Wide 6V to 38V supply range, low 100µV (max) input offset voltage, drives 1nF loads	Wide operating voltage range and precision performance under most capacitive loads provide signal processing in wide range of applications.
Hall-Effect Sensor Interface			
MAX9621	Dual, 2-wire Hall-effect sensor interface	Analog and filtered digital outputs, high-side current sense, 60V capability, detects short to ground fault	Integration eases motor control design.
Temperature Sensors			
MAX31723	Digital thermostat with SPI/3-wire interface	No external components, -55°C to +125°C measurement range, ±0.5°C accuracy, configurable 9- to 12-bit resolution, nonvolatile thermostat thresholds	Eases processor burden by storing temperature thresholds internally in nonvolatile memory.
MAX31855	Thermocouple-to-digital converter	Cold-junction compensated; works with K, J, N, T, or E types; 14-bit, SPI interface; -270°C to +1800°C	Simplifies system design while providing flexibility for various thermocouple types.
Variable Reluctance (VR) Sensor Interface			
MAX9924–MAX9927	Reluctance (VR or magnetic coil) sensor interfaces	Integrated precision amplifier and comparator for small-signal detection, flexible threshold options, differential input stage, zero-crossing detection	Improve performance by accurately detecting position and speed of motors and rotating shafts.
MOSFET Drivers			
MAX15012	Half-bridge gate driver for high- and low-side MOSFETs with 2A peak source/sink current drive	UVLO, fast (35ns typ) and matched (8ns max) propagation delays, 175V high-side MOSFET voltage capability	Prevents MOSFET damage due to supply brownout; allows higher frequency switching applications; allows use in high voltage applications.
MAX15024	Low-side, 4A MOSFET drivers	Single/dual operation, 16ns propagation delay, high sink/source current, 1.9W thermally enhanced TDFN package	Shrinks designs with small package and allows fast switching with tightly matched propagation delays.

(Continued on following page)

Part	Description	Features	Benefits
Interface Transceivers			
MAX13448E	Fault-protected RS-485 transceiver	±80V fault protected, full-duplex operation, 3V to 5.5V operation	Makes equipment more robust and tolerant of misconnection faults.
MAX14840E	High-speed RS-485 transceiver	40Mbps data rates, ±35kV (HBM) ESD tolerance, 3.3V, +125°C operating temperature, small 3mm x 3mm TQFN package	High receiver sensitivity and hysteresis extend cable lengths in harsh motor control environments.
MAX14770E	PROFIBUS transceiver	±35kV (HBM) ESD protection, -40°C to +125°C temperature range, small 3mm x 3mm TQFN package	Industry's highest ESD protection makes motor control more robust.
MAX13171E/3E/5E	Multiprotocol data interface chipset	Complete RS-232 and related protocols equipment interface solution, up to 40Mbps, true fail-safe receivers, ±15kV ESD protection	Enable flexible interfaces with pin-selectable protocols.
MAX13051	CAN transceiver	±80V fault protection, autobaud, ISO 11898 compatible, up to 1Mbps, -40°C to +125°C operation	Provides robust industrial strength CAN interface solution.
Voltage Supervisors			
MAX16052/3	High-voltage supervisor	Adjustable voltage thresholds and timeout; V_{CC} to 16V and open-drain output to 28V	Ease supervisory designs for industrial applications with high-voltage capability.
MAX6495	72V overvoltage protector	Protects against transients up to 72V, small 6-pin TDFN-EP package	Increases system reliability by preventing component damage from high-voltage transients.
Control Interfaces			
MAX6816/17/18	Single, dual, octal switch debouncer	±15kV ESD (HBM) protection	Assure high reliability, clean pushbutton signal from motor control panels.
MAX7370	Key-switch controller plus LED backlight drive with dimming	Up to 64-key, separate press/release codes, ±14kV Air Gap ESD, LED drive with PWM dimming control and blink, optional GPIO	Enables high reliability keyboard scanning and display illumination in one IC.
MAX16054	Pushbutton on/off controller with debounce and ESD protection	Handles ±25V input levels, ±15kV ESD, deterministic output on power-up, no external components	Enables simple, robust control panel interface in small SOT23 package.
MAX6971	16-port, 36V constant current LED driver	25Mb 4-wire serial interface, up to 55mA current per output, fault detection, high dissipation package, -40°C to +125°C operation	Eases design of robust control panel indicators.
UARTs			
MAX3108	Serial UART, SPI, I^2C compatible	24Mbps (max) data rate, 128-word FIFOs, automatic RS-485 transceiver control, 4 GPIOs, 24-pin SSOP or small 3.5mm x 3.5mm TQFN packages	Reduces host controller performance requirements and cost.

Calibration and Automated Calibration

The goal of calibration is to maintain a piece of equipment in its most accurate state. The goal of automated calibration is to improve efficiency and consistency of the calibration process, while minimizing the down time required to verify equipment performance.

Accuracy vs. Precision

The terms accuracy and precision are often used synonymously, but they are not the same thing. Both are, however, needed to achieve the best results. We can illustrate the differences between these two terms through the following example. To measure the performance of a particular system, one can plot the results of a large number of samples over time on a graph and note the differences between the actual results and the desired result (**Figure 1**). Accuracy is the measure of how close the mean of the total set of results is to the desired result. Precision is a measure of the spread of these results relative to this mean. Precision only addresses how dispersed the results are, not how far they are from the average of the desired value.

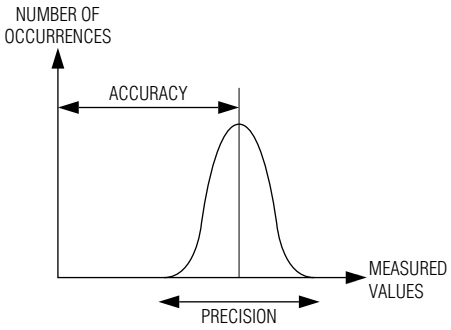


Figure 1. Accuracy and precision are two very different things.

Calibration

Calibration usually addresses accuracy and less often precision. From the above discussion it is evident that calibration may not have any effect on precision, because other circuit parameters such as noise may have an influence on precision and no amount of calibration will reduce the spread of values. This is of course not always the case, such as in light beam focusing. When a beam is correctly focused, its spread is reduced. This is, of course, not always the case.

For complete basic calibration, it is often required to correct for both offset and span (gain). This requires calibration at more than one point. If a system is linear, calibration at two points will suffice since two points define a line (**Figure 2**). If a system is nonlinear, more calibration points are needed.

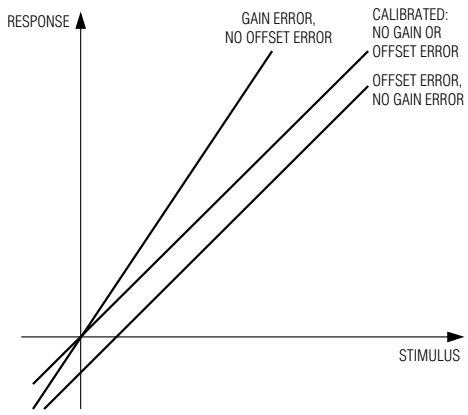


Figure 2. For proper basic calibration, the system response to stimuli must be corrected for both offset and gain errors. Offset errors do not produce a zero output for a zero input. Gain errors (when no offset error remains) show more deviation from the expected results at larger input stimuli.

Calibration is the process of adjusting circuit parameters, such as offsets and gains, to make equipment meet specifications or a standard. All organizations producing electronic goods must either design with high-precision components or use some form of calibration.

All electronic products must pass at least minimal signal testing prior to shipping to ensure that the product works out of the box. A rigorous test and calibration process also reduces liability from performance errors and provides a paper trail that shows that industry and regulatory requirements have been followed.

Although new products may meet strenuous requirements for calibration, due to the effects of use, wear, and environmental conditions, over time products may no longer meet specifications. For some products the effect is easily seen: a cell phone that no longer receives calls, or a hard drive that loses data. For others, e.g., a voltmeter with a small drift, the effect cannot be easily seen, but the impact may be costly. Or, in the case of an insulin pump, the impact may be even dangerous. For many types of industrial (and medical) electronic equipment, calibration is an on-going process and is the reason why many products are now being designed with self-calibration circuitry.

For control devices used in a production environment, a proper calibration process uses test equipment that has been certified to standards traceable to a government agency. In the U.S. this agency is the National Institute of Standards and Technology (NIST). This type of certified calibration requires the services of a certified metrology lab. The lab will not only calibrate the equipment based upon recognized standards, but will also provide reports as part of their service. These reports prove that the equipment has been measured and adjusted relative to a chain of standards traceable back to the government's master standards.

Test Equipment Calibration

While calibration of the end product is required to establish its performance, the production test equipment used to calibrate it must, of course, also be operating within its specifications (**Figure 3**). This calibration is maintained with more accurate test equipment and reference standards used only occasionally for this purpose. Eventually these standards must also be calibrated. As one moves further back in the chain, the equipment gets more accurate and more sensitive, usually by an order of magnitude or at least 4:1 at each stage, so it must be treated with more care to avoid "knocking" it out of calibration.

Today test equipment is being built with new techniques that reduce or eliminate calibration expenses or downtime. These techniques, called electronic or automated calibration, use self-calibration or digital calibration.

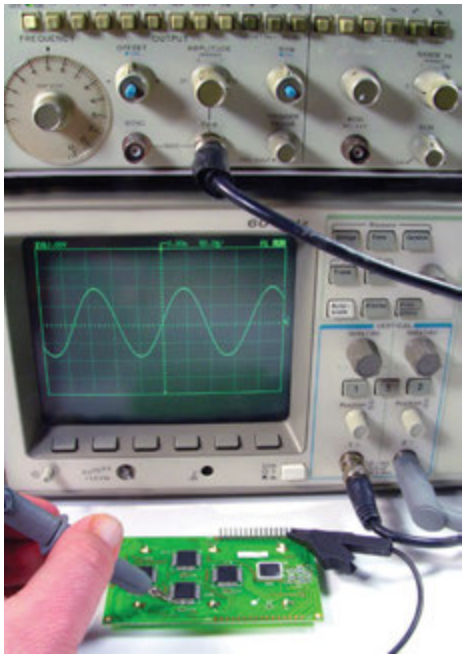


Figure 3. An oscilloscope has many functions to be calibrated in the instrument and on the probe itself. Voltage probes usually have a compensation adjustment for proper frequency response. A true square wave is generated by the scope to test this probe setting. Internal self-tests and self-calibrations are common, but use of known good external standards is still periodically needed for calibration certification.

Benefits of Automated Calibration

Automated calibration can reduce cost in many areas. It does this by removing manufacturing tolerances, allowing the use of less expensive components, reducing test time, improving reliability, increasing customer satisfaction, reducing customer returns, lowering warranty costs, and increasing the speed of product delivery.

Automated Calibration Characteristics

Automated calibration is built around circuitry that is designed into the end equipment for the explicit purpose of maintaining calibration. This circuitry can take a variety of forms and functions. For example, this circuitry could utilize digital communication between the end equipment and a remote host or a factory test system. Once communication is established, the end equipment uploads data to the host and then through commands and downloaded data, the host calibrates the end equipment's circuit parameters. Or, the circuitry could be completely internal to the equipment itself. In this latter case, the circuitry might measure an imbedded precision component, such as a precision resistor or voltage reference, to allow adjustment and verification of the accuracy of the signal chain components.

Testing and calibration generally fall into three broad areas:

1. Production-line final-test calibration
2. Periodic self-testing
3. Continuous monitoring and readjustment

Automated and electronic calibration can be cost effective in each area.

Final-Test Calibration

When a circuit is developed in the lab, typically 20 to 50 devices are prototyped and tested. All signal levels are measured, and variances and tolerance margins are noted. However, when the product goes into production, hundreds of thousands or even millions of devices are built and they do not receive the same level of testing for proper signal levels, variances, and tolerance margins.

All practical components, both mechanical and electronic, have manufacturing tolerances. The more relaxed the tolerance, the more affordable the component. When components are assembled into a system, the individual tolerances accumulate to create a total system error tolerance. When thousands of devices are manufactured, the errors can multiply so that a properly manufactured product may not work. If this happens enough to reduce yields, then profitability is affected. Through the proper design of trim, adjustment, and calibration circuits, it is possible to correct for the worst-case tolerance stackups, thereby ensuring that a higher percentage of products can be made to meet specifications upon exiting the assembly line.

Final-test calibration corrects for these errors. Multiple adjustments may be required to calibrate the device under test (DUT) to meet specifications.

For example, suppose the design engineers find that they can use ±5% resistors and a low-cost op amp because their Monte Carlo testing shows that even under worst-case tolerance stackup, the use of two low-cost digital potentiometers (pots) for offset and gain can calibrate out all the variation from the components chosen. They also see that to eliminate the adjustability altogether, they would have to use expensive tight tolerance resistors and a precision op amp. With this knowledge, they decide to use the circuits as-is and to simply adjust the offset and span (gain) during final test to meet system specifications. By using digital pots instead of mechanical pots, they avoid using human labor to make the adjustments.

Periodic Self-Testing

Environmental influences in the field can create a need for test and calibration.

Such environmental factors include temperature, humidity, vibration, contamination, and component aging. These factors are accounted for with a combination of self-test at power-up and periodic or continuous testing. The field testing can be as simple as sensing temperature and compensating accordingly, or it can be more complex.

A simple example of power-up self-testing is to automatically briefly short the inputs of an amplifier together to set a zero reading point (**Figure 4**). Doing so allows any changes to input offset voltage or to downstream circuit parameters to be calibrated out. Another example is to electronically swap the resistive temperature sensor with a precision fixed resistor to enable the instrument to calibrate the temperature reading to the expected value. Using two different precision resistors can establish a line that provides both gain and offset information. More complex schemes can be used to adjust for nonlinearities.

Figure 4. A digital multimeter showing good calibration of the zero signal level, but is the gain calibrated? This is difficult to discern without a reference standard to read periodically. Or, maybe during power-up it reads a precision internal value while the display is blanked to check for proper gain calibration?

Continuous Monitoring and Readjustment

In some applications, waiting for periodic calibration at power-up would occur only very rarely after system maintenance which can be too costly if system performance is suffering or safety margins are compromised from an out of calibration component. Depending on the impact of a system not being calibrated, these applications may need to use continuous monitoring with subsequent readjustment. Good examples of applications that requires continuous monitoring and calibration are a variety of safety systems in nuclear power plants.

Continuous calibration consists of circuitry that self-corrects continuously or very frequently. This can be accomplished in a variety of ways either with techniques similar to periodic self-testing, just done more frequently, or with other techniques that allow the system to continue to operate. In the former case, very brief interruptions to the normal signal path may be made, including making connections to simulate zero scale and full scale readings for example. Another use of these interruptions would be, for example, to cut a signal path gain in half and check that the response is indeed exactly half. If not, an offset error is indicated and can be corrected for. In the latter case, where full system operation needs to be maintained, out-of-band or noise level techniques can be used by injecting signals either above or below the normal signal frequency range, or signals so small that they fall within the noise floor of the system. With proper design, these signals are detectable by a variety of methods. These can be used to stimulate the test and calibration protocol while standard signal processing continues. The techniques used are limited only by the creativity of the engineers. If a system, during a readjustment, detects that no further adjustment is possible, then an alarm condition must be set.

The ability to adjust analog outputs using digital technology has greatly enhanced the ability to continuously monitor and adjust. Digital technology provides low-cost and nearly error-free communications for remote monitoring and subsequent control. Digital control of analog circuitry using precision DACs and digital pots allows economical remote-control processes, while also ensuring the precision needed to meet specifications.

Circuitry for Electronic and Automated Calibration

Electronic calibration is based on digitally controlled calibration devices: DACs with voltage or current outputs can be used to provide temporary inputs to analog signal chains or to adjust bias levels. Digital pots with variable resistances or variable resistance ratios can provide gain and offset adjustments, analog switches can select different gain or filter corner setting components, and potentially any other digital-to-analog transducer such as a digitally controlled light source can be used to stimulate a self-calibration process. All of these replace mechanical calibration procedures in factory settings and within the equipment itself. The digital approach provides a range of benefits: better reliability, improved employee safety, increased dependability, and reduced product liability expense. In addition, digitally controlled calibration can be fully automated, which results in reduced test time and expense by removing human error.

Solid state solutions such as digital pots as opposed to mechanical pots are not susceptible to mechanical shock and vibration, which can cause loss of calibration settings and, in the case of mechanical pots, can cause momentary wiper contact bounce which will likely lead to unpredictable and potentially dangerous behavior.

Analog switches have improved to the point that their on-resistance is low enough that they can be used in high-precision gain setting circuits to provide a range of precision fixed-gain choices. This capability, combined with a digital pot for fine adjustments within a gain range, can provide an extremely precise calibration capability.

Implementing Electronic Calibration

Digital pots, which can guarantee 50,000 write cycles, allow periodic adjustments to occur repeatedly over long equipment life spans. Conversely, the best mechanical pots can support only a few thousand adjustments. Location flexibility and size are also advantages. Digitally adjustable pots can be mounted on the circuit board directly in the signal path, exactly where they are needed. In contrast, mechanical pots require human access, which can necessitate placing them in nonoptimal locations that result in long circuit traces or with designers having to resort to using coaxial cables to make the proper noise-shielded connections. In sensitive circuits, the capacitance, time delay, or interference pickup of these connections can reduce equipment precision.

Digital pots used in electronic calibration schemes can be fundamental in eliminating these types of problems. In addition, calibration DACs (CDACs) and calibration digital pots (CDPots) also enable electronic trimming, adjustment, and calibration. These calibration-specific devices often employ internal nonvolatile memory, which automatically restores the calibration setting during power-up and provides the ability to customize the calibration granularity to match the application.

For extra safety, one-time programmable (OTP) CDPots are available. These devices can permanently lock in the calibration setting, preventing an operator from making further adjustments. To change the calibration value, the device must be physically replaced. A special variant of the OTP CDPot always returns to its stored value upon power-on reset, while allowing operators to make limited adjustments during operation at their discretion.

Leveraging Precision Voltage References for Digital Calibration

Sensor and voltage measurements with precision ADCs are only as good as the voltage reference used for comparison. Likewise, output control signals are only as accurate as the reference voltage supplied to the DAC, amplifier, or cable driver.

Common power supplies are not adequate to act as precision voltage references. They typically are not designed to meet the accuracy, temperature coefficients, and noise specifications needed in a voltage reference. All voltage sources have some imperfect specifications for power-supply rejection ratio (PSRR) and for load regulation, but typically a voltage reference will have very good PSRR specifications. The load range allowed is usually far less than a power supply's load range, which reduces its output voltage tolerance. No control system can have infinite gain while remaining stable, so there will always be some loading effect on the output voltage of a voltage reference.

Compact, low-power, low-noise, and low-temperature-coefficient voltage references are affordable and easy to use. In addition, some references have internal temperature sensors to aid in the compensation for this environmental variable. Voltage references with "force" and "sense" pins further improve accuracy by removing the slight voltage effects of ground currents in the circuit.

In general, there are three kinds of serial calibration voltage references (CRefs), each of which offers unique advantages for different factory applications. Having a choice of serial voltage references enables the designer to optimize and calibrate with high accuracy.

The first type of reference, a trimmable CRef, enables a small trim range, typically 3% to 6%. This is an advantage for gain trim in industrial imaging systems. For instance, coupling a video DAC with a trimmable CRef allows the overall system gain to be fine-tuned by simply adjusting the CRef voltage.

The second type, an adjustable reference, allows adjustment over a wide range (e.g., 1V to 12V), which is advantageous for field devices that have wide-tolerance sensors and that must operate on unstable power. Some examples, such as portable maintenance devices, may need to operate from batteries, automotive power, or emergency power generators.

The third type, called an E^2Ref, integrates memory, allowing a single-pin command to copy any voltage between 0.3V and (V_{IN} - 0.3V) and, then, to infinitely hold that level. E^2Refs benefit test and monitoring instruments that need to establish a baseline or warning-alert threshold.

Summary

Electronic and automated calibration techniques are becoming mainstream because they make production more efficient and products last longer. New products like CDACs and lower cost precision DACs, digital pots, and CRefs from Maxim provide an economical way to incorporate calibration circuitry directly into end products to minimize downtime, reduce costs, and improve long-term performance, even under harsh operating conditions.

Recommended Solutions

Part	Description	Features	Benefits
CDPots			
MAX5481	1024-tap (10-bit) CDPot with SPI or up/down interface	1.0µA (max) in standby, 400µA (max) during memory write	Minimal power use for battery-operated portable devices.
MAX5477	Dual, 256-step (8-bit) CDPot with I^2C interface	EEPROM write protection, single-supply operation (2.7V to 5.25V)	EEPROM protection retains calibration data for safety.
MAX5422	Single, 256-step (8-bit) CDPot with SPI interface	Tiny (3mm x 3mm) TDFN package	Saves PCB space for portable products.
MAX5427	32-step (5-bit), OTP CDPot	OTP or OTP plus adjustment	Versatile, reduces component count by performing two functions.
DS3502	128-step (7-bit) CDPot with I^2C interface	High output voltage range (up to 15.5V)	Permits direct calibration of high-voltage circuits.
CDACs			
MAX5105, MAX5115	Quad, 8-bit CDACs with independent high and low reference inputs	Rail-to-rail output buffers, choice of I^2C or SPI interface	Selectable voltage range improves granularity and prevents unsafe adjustments.
MAX5106	Quad, 8-bit CDAC with independently adjustable voltage ranges	Allows customization of calibration granularity, small 5mm x 6mm package	Saves PCB space for portable products.
MAX5214/MAX5216	Ultra-low-power, 1-channel, 14-/16-bit voltage-output DACs	Quiescent current < 80µA max, SPI interface	High resolution and external reference provides fine granularity and flexibility for automated calibration systems.
MAX5715*	Quad, 8-/10-/12-bit DACs with internal reference	8-/10-/12-bit voltage-output DAC, three-voltage-selectable internal reference, SPI interface	High integration provides multiple calibration points in a small space.
MAX5725*	Octal, 12-bit DAC with watchdog timer and internal reference	8-/10-/12-bit resolution, selectable internal reference, watchdog timer, SPI interface	Watchdog timer allows resets to defined calibration levels in event of communication failure.
CRefs and E^2Refs			
MAX6160	Adjustable CRef (1.23V to 12.4V)	Low 200mV dropout, 75µA supply current is virtually independent of input-voltage variations	Longer battery life in portable equipment.
MAX6037	Adjustable CRef (1.184V to 5V)	Shutdown mode (500nA, max), low 100mV (max) dropout at 1mA load, 5-pin SOT23 ($9mm^2$)	Battery friendly and small size for portable applications.
MAX6173	Precise voltage reference with temperature sensor	±0.05% (max) initial accuracy, ±3ppm/°C (max) temperature stability	Allows analog system gain trim while maintaining the digital accuracy of ADCs and DACs.
MAX6220	Low-noise, precision voltage reference	8V to 40V input-voltage range, ultra-low $1.5\mu V_{P-P}$ noise (0.1Hz to 10Hz)	Dependable operation from unstable power (batteries, automotive power, or emergency power generators).
DS4303	Electronically programmable voltage reference	Wide, adjustable output voltage range can be set within 300mV of the supply rails with ±1mV accuracy	A calibration voltage is memorized forever using one simple GPIO pin.

*Future product—contact the factory for availability.

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